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Renewable fuel alternatives for mobile machinery

A short study commissioned by
Fachagentur Nachwachsende Rohstoffe e.V. (FNR)

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AFID	Alternative Fuels Infrastructure Directive
BTL	Biomass to liquid
CNG	Compressed natural gas
DPF	Diesel particle filter
ETS	Emission Trade System
FAME	Fatty acid methyl ester
FNR	Fachagentur Nachwachsende Rohstoffe e. V.
FQD	Fuel quality directive
HVO	Hydrotreated vegetable oil
ILUC	Indirect land use change
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
NREAP	National Renewable Energy Action Plan
NRMM	Non road mobile machinery
PVO	Pure vegetable oil
RED	Renewable energy directive
SCR	Selective catalytic reduction
TREMOD-MM	Transport Emission Model – Mobile Machinery

Executive summary (English)

Mobile machinery makes a significant contribution to the total transport emissions in Germany, emitting 15 Mt of CO_2 in 2015 (corresponding to 9% of the emissions of road transport) and an even higher share of NOx -24% of road emissions- and PM -120% of road emissions. Reducing emissions is therefore of high importance, also in the light of climate protection goals. The use of renewable alternative fuels in mobile machinery opens up the opportunity to reduce GHG emissions in the sector. The corresponding challenges and potentials are discussed in the present short study commissioned by the Fachagentur Nachwachsende Rohstoffe e.V. (FNR).

As three main renewable fuel alternatives biodiesel (blend or pure biofuel/vegetable oil), biomethane and electricity have been identified and are further analysed:

- Biodiesel (B7) is a low hanging fruit because it relies on a very good infrastructure (available in all fuel stations) and a perfect compatibility to all existing diesel vehicles. The potential environmental impact is limited by the blending (7% in volume), which offers a maximum potential consumption of 370 million litres of biofuel out of over 5 billion litres of diesel consumed by NRMM in 2015.
- Higher blends of biodiesel (for example B20 and at the highest level B100 or its oil equivalent: pure vegetable oil (PVO)) can bring considerable additional emission savings i.e. depending on the feedstock up to 85% on a life cycle basis. Nevertheless the infrastructure availability for high blends is limited, so that using this kind of oil or biodiesel requires a local production (for example PVO for agriculture) or private pumps.
- At the other end of the spectrum is electricity, showing the best environmental potential (if renewable electricity is used). It also ranks very well in terms of energy costs. The main obstacles are the currently growing but still limited availability of e-vehicles or e-machinery compared to such powerd by diesel engines.
- Finally CNG with a high share of biomethane is a possible alternative to petroleum products, but the environmental impact varies much according to the share of biomethane and the feedstock used. Biomethane availability is limited and the public infrastructure still relies heavily on fossil gas. Nevertheless, first models of mobile machinery powered by gas are being produced and tested.

In total it is assumed that by technical means up to 2,300 kt of diesel fuel could be substituted by biofuels which is more than 50 % of the total diesel consumption of mobile machinery. The agricultural sector clearly makes the largest contribution due to an assumed high potential for B100 or PVO. In practice, however, only a small share of these potentials is likely to be realised in the near future due to issues of compatibility of the fuels with current vehicles, infrastructure availability, local production facilities and energy costs.

Executive summary (German)

Mobile Maschinen tragen erheblich zu den gesamten Verkehrsemissionen in Deutschland bei. Der Anteil lag bei CO_2 mit 15 Mt in 2015 bei 9 % der Emissionen des Straßenverkehrs und war bei NOx mit 24 % und PM mit 120 % der Straßenverkehrsemissionen noch höher. Die Reduzierung dieser Emissionen ist auch vor dem Hintergrund der Klimaschutzziele wichtig. Die Nutzung alternativer und erneuerbarer Energieträger in mobilen Maschinen ist eine Möglichkeit um die Treibhausgasemissionen in diesem Sektor zu verringern. Die jeweiligen Potenziale und Herausforderungen werden in der vorliegenden Kurzstudie diskutiert, die im Auftrag der Fachagentur Nachwachsende Rohstoffe e.V. (FNR) erstellt wurde.

Drei grundsätzliche Kraftstoffalternativen wurden identifiziert und weitergehend analysiert: Biodiesel (Beimischungen und Reinkraftstoff), Biomethan und erneuerbarer Strom.

- Biodiesel als Beimischung (B7) ist der einfachste Weg, da er auf einer guten bestehenden Infrastruktur (verfügbar in allen Tankkstellen) basiert und kompatibel zu den bestehenden Dieselmaschinen ist. Das Klimaentlastungspotenzial durch Beimischung (7vol%) ist dabei jedoch begrenzt, da bei insgesamt über 5 Milliarden Liter Dieselverbrauch (2015) bei mobilen Maschinen nur maximal 370 millionen Liter Biodiesel eingesetzt werden können.
- Höhere Beimischung (B20 bis B100 bzw. reines Pflanzenöl) können zu deutlich größeren Treinhausgaseinsparungen führen, der Vorteil ggü. fossilem Diesel über den Lebensweg liegt je nach Primärmaterial bei bis zu 85%. Die Infrastruktur für den Einsatz ist jedoch begrenzt, so dass die Nutzung von Pflanzenöl oder B20 eine lokale Produktion (z.B. Pflanzenöl in der Landwirtschaft) oder eigene Zapfsäulen erfordert.
- Auf der anderen Seite zeigt Elektrifizierung das höchste Umweltentlastungspotenzial, wenn erneuerbarer Strom zum Betrieb der mobilen Maschinen genutzt wird. Strom ist auch bezüglich der Energiekosten vorteilhaft. Das größte Hemmniss ist die immer noch stark limitierte Verfügbarkeit von elektrisch betriebenen Maschinen im Vergleich zu Maschinen mit Dieselmotor.
- Schlussendlich ist auch Erdgas (CNG) mit einer hohen Beimischung von Biomethan eine möglich alternative zu fossilen Kraftstoffen, der Umweltentlastungseffekt hängt jedoch stark vom Beimischungsanteil und dem Primärmaterial ab. Biomethan verfügbarkeit ist zudem begrenzt und die öffentliche Infrastruktur noch immer stark auf fossiles Erdgas fokussiert. Nichtsdestotrotz werden erste mobile Maschinen mit Gasantrieb produziert und getestet.

Es wird davon ausgegangen, dass in mobilen Maschinen technisch bis zu 2.300 kt Dieselkraftstoff durch Biokraftstoffe ersetzt werden könnten, mehr als 50% des gesamten Dieselverbrauchs. Die Landwirtschaft hat hierbei den größten Anteil, da hier ein hohes Potenzial für Nutzung von B100 und Pflanzenöl gesehen wird. In der Praxis stehen der Ausschöpfung dieses Potenzials jedoch noch Kompatibilitätsprobleme mit aktuellen Maschinen, begrenzte Verfügbarkeit von Infrastruktur und lokalen Produktionsanlagen sowie Energiekosten entgegen.

1 Introduction

Mobile machinery make a significant contribution to total transport emissions in Germany, emitting 15 Mt of CO_2 in 2015 (corresponding to 9% of the emissions of road transport) and an even higher share of NOx – 24% of road emissions- and PM -120% of road emissions. This is due to less strict emission limits, which have been implemented later than for road transport, and a relatively old vehicle fleet. In this context there is an urgent need for action to reduce the pollutant emissions. In light of the climate protection goals, also greenhouse gases (GHG) of mobile machinery need to be considerably reduced. The use of renewable alternative fuels in mobile machinery is a way to reduce GHG emissions in this sector – the possibilities and potentials are discussed in this short study commissioned by Fachagentur Nachwachsende Rohstoffe e.V. (FNR).

As a driver, the EU Energy roadmap [European Commission, 2011] aims at decarbonising the EU economy with a 80% reduction of total GHG emissions compared to 1990 and a minimum share of 55% renewable energy sources (RES) in gross final energy consumption by 2050. Several directives have been implemented to help reaching these goals in the transport sector:

- the Renewable Energy Directive (RED), aiming at achieving 20% of RES in the EU gross final energy consumption by 2020
- the Fuel Quality Directive (FQD), requiring the reduction of fuel related GHG emissions of 6% by 2020 compared to 2010
- the alternative fuel infrastructure directive (AFID), expecting from the Member States a strategy to develop an appropriate infrastructure for CNG, LNG, hydrogen and electricity by 2020-2030.

The present reports starts by describing the mobile machinery sector in terms of fuel consumption and emissions in Germany (chapter 2). The calculation of emissions from mobile machinery in Germany has been undertaken with „TREMOD-MM“ (Transport Emission Model - Mobile Machinery), a tool developed by ifeu on behalf of the German Federal Environment Agency. Afterwards policies targeting the emission behaviour of mobile machinery are discussed at different levels:

- The overall EU legislative framework impacting the penetration of alternative fuels in all sectors and the emissions of mobile machinery (chapter 3.1)
- National, regional and municipal environmental policies targeting mobile machinery with a focus on the agricultural (chapter 3.2) and construction (chapter 3.3) sectors

In the last chapter (Chapter 4) the opportunities for using renewable fuels in non-road mobile machinery are discussed with a focus on biofuels, electricity and biomethane.

This short study aims at giving a clear overview of the framework, challenges and opportunities of using renewable energy sources for non-road mobile machinery. Further research may be required for an in-depth analysis of selected solutions.

2 Status quo of mobile machinery emissions in Germany

Official reporting obligations for emissions from non road machinery in Germany are fulfilled by the German Federal Environment Agency (Umweltbundesamt = UBA). In order to fulfil these obligations, the Institute for Energy and Environmental Research (ifeu) has developed a differentiated inventory model. This model complemented the already existing model TREMOD (Transport Emission Model) for the transport sector and is referred to as TREMOD-MM (MM for Mobile Machinery). TREMOD MM is a Microsoft Access based tool considering the structure of current emission regulation, relying on highly differentiated and transparent input data; future emissions can be calculated for different scenarios.

The main input data for TREMOD-MM are updated annually on behalf of the Federal German Environment Agency (UBA). Further developments of methodology, machinery and pollutant coverage are undertaken in the form of projects at irregular intervals, depending on the legislative, political and industry requirements.

Mobile machinery are dominated by diesel engines: According to TREMOD-MM, diesel fuel consumption was in 2015 about 4.4 million Tonnes, while gasoline consumption was slightly over 0.1 million Tonnes. Almost 15 Mt of CO_2 emissions are caused by mobile machinery in the considered sector (see Table 1), which is about 9 % of road transport emissions (see Figure 1). Regarding emissions of pollutants, however, the contribution of mobile machinery is considerably higher, for NO_x it amounts to 24 % (98 kt) of the road transport emissions, slightly over 30 % for CO (230 kt) as well as HC (31 kt) emissions and up to 120 % of the road PM emissions (10 kt) as shown in Figure 1. Particle number (PN) is often used as indicator for ultrafine particles, which pose serious health risks. In 2015 mobile machinery emitted ~ $3*10^{19}$ particles which is 3.5 times more than road transport [ifeu, 2015].

Table 1: Total TTW emissions of mobile machinery in Germany in 2015

Germany 2015 (kt)	CO_2	NOx	PM	CO	HC
Construction	5,511	27	2.0	56	4.0
Recreational Boats	163	1.3	0.1	4.0	0.5
Forestry	378	1.6	0.1	8.5	1.7
Household / Gardening	303	0.5	0.1	109	13
Industry / Other	1,667	15	0.6	5.7	1.7
Agriculture	6,774	53	7.5	46	10
Total	14,796	98	10	230	31

The comparatively high contribution of mobile machinery to criteria pollutants compared to the low fuel consumption and CO_2 emission share is mainly due to emission limits being introduced much later and being less strict for mobile machinery than for road vehicles. For example, EU engine certifiation standards require to use diesel particle filters (DPF) for most mobile machinery from 2019 on (refer to chapter 3) but diesel cars and trucks already need filters since 2013 or even earlier. Furthermore, many machinery (especially in agriculture) tend to have a very long operational life compared to road vehicles, leading to an ageing vehicle park. Accordingly, mobile machinery make a significant contribution to air pollution, but are also relevant in respect to greenhouse gas emissions.

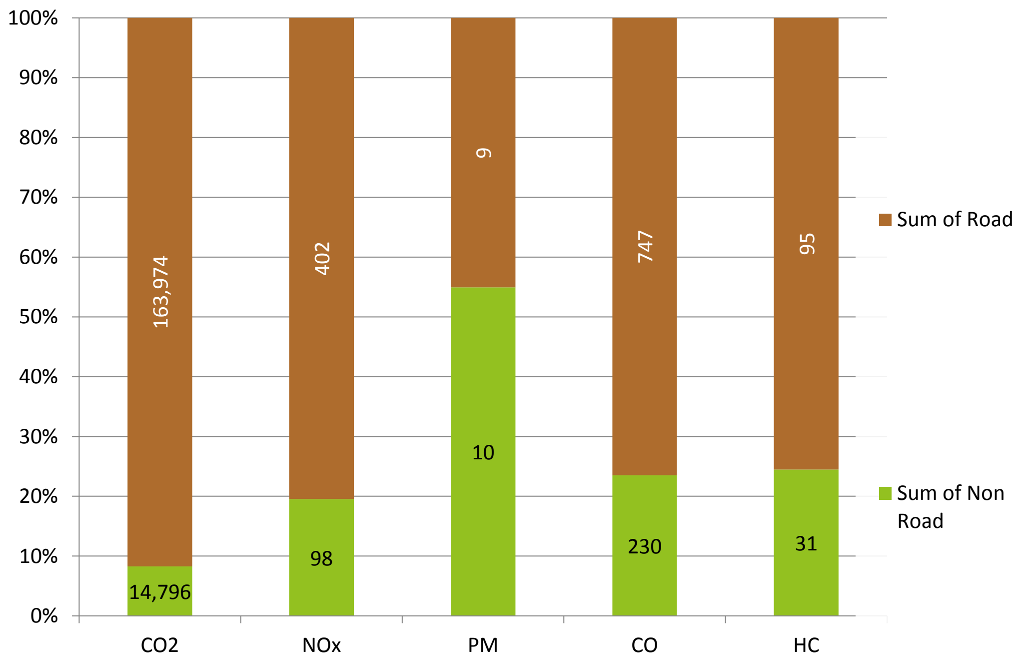


Figure 1: Comparison of road and non-road emissions in Germany 2015 (total values in kt)

The biggest fuel consumers and CO_2 emitters are the agricultural and construction sectors. Relying mainly on diesel engines, they also emit the majority of NOx and PM emissions (see Figure 2). CO and HC emissions in turn are rather dominated by gasoline engines which clearly make a large contribution despite the significantly smaller fuel consumption compared to diesel engines.

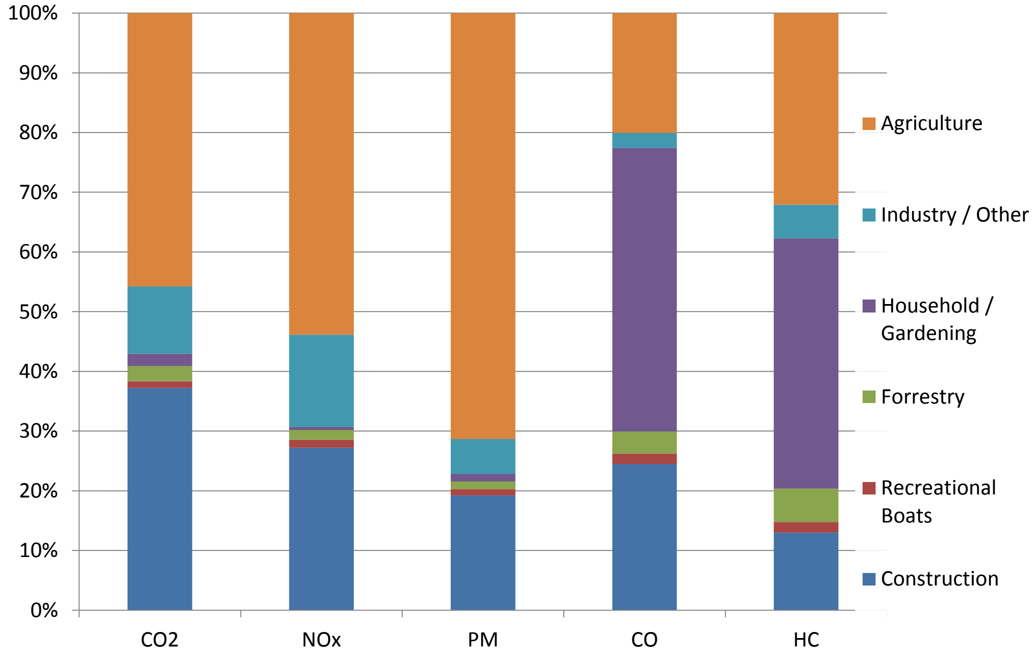


Figure 2: Share of different sectors on total non road emissions in Germany 2015 (total values see Table 1)

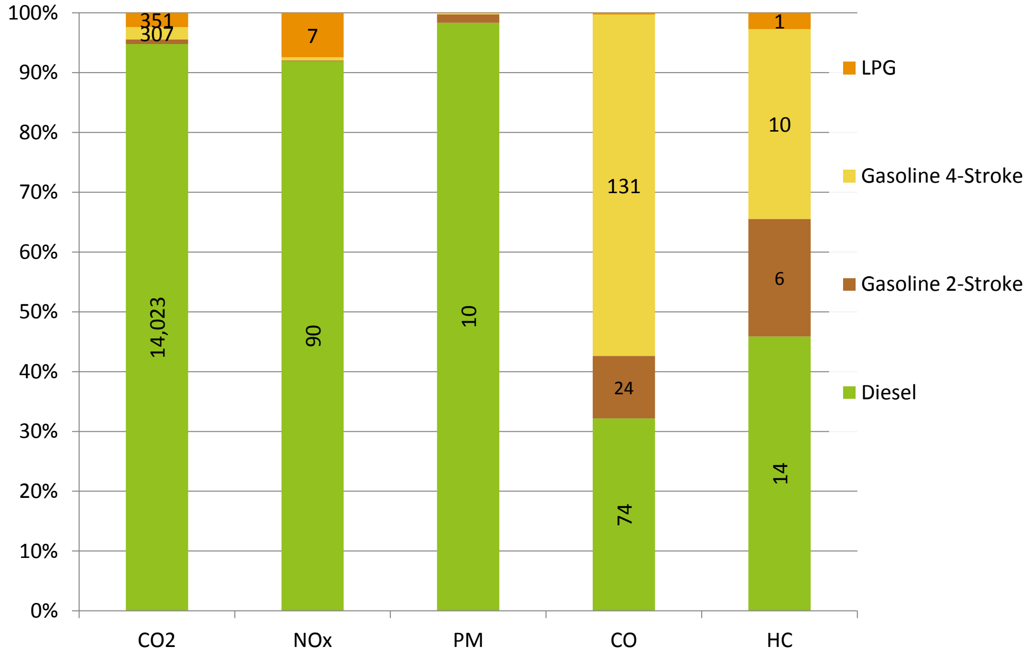


Figure 3: Share of different engine types on total non-road emissions in Germany 2015 (total values in kt)

PM and NOx emissions is currently regarded as most critical for air quality management. Figure 4 shows that NOx emissions in agriculture are dominated by diesel engines of larger power classes, which are responsible for an even larger share of these emissions in the construction industry. In the agricultural sector, the official stock statistics show that a lot of old machinery of medium power is still in registered. But in fact those are quite often only used for temporary substitute.

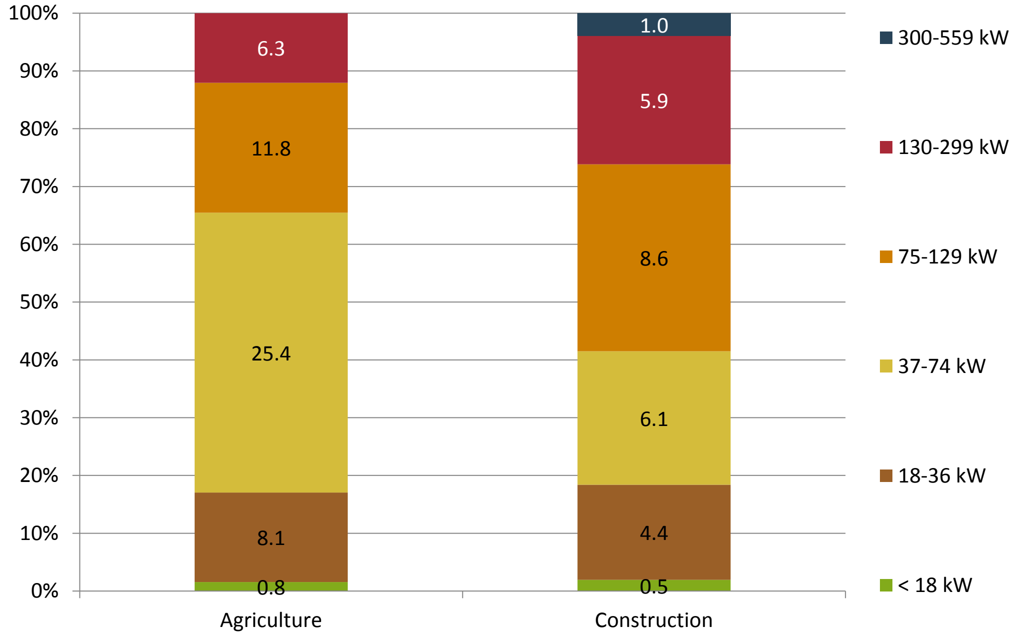


Figure 4: Share of different power classes on total NOx emissions in the agricultural and construction sector (total values in kt)

3 Policies for non-road mobile machinery

Non-road mobile machinery in Germany is subject to the European emission regulation specified in Regulation 2016/1628 –setting the requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC. For diesel machinery, stage I to IV have already been introduced and Stage V (Regulation 2016/1628) will be effective from 2019 or 2020 onwards (depending on the type of motor). The EU regulation covers only pollutant emissions; so far no regulation of CO_2 emissions for mobile machinery is planned.

The agricultural sector has the highest share on mobile machinery diesel fuel consumption and is being largely operated out of urban areas. Therefore further national policies for the agricultural sector focus on the use of alternative fuels and thus target CO_2 emissions. The construction sector on the other hand, is also making a relevant contribution to urban PM_{10} and NO_2 pollutant concentrations (see [ifeu, 2014a], [ifeu, 2014b]), thus regional and local measures focus on the use of after treatment systems and the early introduction of clean emission standards, targeting pollutant emissions.

3.1 The EU legislative framework

The main alternatives to fossil diesel fuel in the agricultural (and forestry) sector are biodiesel or vegetable oils. These are subject to different international and national regulations. On the EU level, the main directives are the Renewable Energies Directive [EU, 2009], the Fuel Quality Directive [EU, 2012] and the indirect Land Use Change directive [EU, 2015] all aiming at increasing the share of renewable energy in the EU and decreasing the GHG emissions of fuels. Adding to those, two overarching directives intend to foster the use of sustainable fuels and to diversify the European energy mix: the Effort sharing decision, giving the GHG emission reduction goals for non ETS sectors and the Alternative Fuel Infrastructure Directive, aiming at pushing the penetration of alternative fuels. A summary of these directives are given in Table 2.

Table 2: Summary of the main EU policies concerning transport emissions

Policies	Description
Renewable Energy Directive - RED (2009/28/EC)	20% of RES in the EU gross final energy consumption by 2020 (each country having its own goal) RED II (period 2021-2030) under consultation plans to limit food-based biofuels and push advanced biofuels for transport and strengthens

	RES share: 27% by 2030
Fuel Quality Directive – FQD (98/70/EC and 2009/30/EC)	Reduction of fuel related GHG emissions of 6% by 2020 compared to 2010 (life cycle analysis of GHG emissions in g CO_2-eq per MJ compared with fossil reference fuels)
Indirect Land Use Change Directive - iLUC (EU 2015/1513)	Cap of 7% on the contribution of biofuels produced from 'food' crops (1st generation) by 2020 0.5% minimum contribution of advance biofuels
Effort sharing decision (Decision 406/2009/EC)	5% of GHG emission reduction for non ETS sectors (2020 vs. 2005); A follow up regulation is currently discussed incl. a proposal of a GHG emission reduction of 24% (2030 vs. 2005)
Directive on the Deployment of Alternative Fuels Infrastructure - AFID (2014/94/EU)	Appropriate number of refuelling stations for CNG, LNG or hydrogen and electricity recharging stations by 2020-2030 depending on the transport mode and fuel type.

Renewable Energies Directive [EU, 2009]

The RED sets a goal of 20% of RES in the final energy consumption together with a 20% increase in energy efficiency by 2020. Concerning transport, it ambitions a market share of 10% of RES or renewables energy sources (based on the net calorific value). It has been completed by the iLUC directive (see below). It must be noted that according to the RED liquid produced from biomass used in other sectors than transport are named “bioliquids”. The same sustainability criteria as for biofuels apply to them i.e. any bioliquid used in non-transport sectors but contributing to the FQD GHG savings target need to meet the same sustainability criteria as biofuels used by transport. Even if bioliquids used in non-road mobile machinery do not count towards the RED transport target they count towards the overall RED target [Skinner, et al., 2010]. A follow-up of the current RED is under consultation at the time of the present report. It strengthens the share of RES, reaching 27% in 2030 and goes from the 7% cap of food-crops biofuels and bio liquids in 2020 to 3,8% by 2030 [BBEE-Kompetenzzentrum Europa, 2016]. According to the German Federal Ministry for Economic Affairs and Energy the reference scenario of the NREAP (National Renewable Energy Action Plan) would lead only to share of 18% of RES by 2020, and only an efficiency scenario would allow reaching the 20% [BMWi, 2015].

Indirect Land Use Change directive [EU, 2015]

The indirect Land Use Change Directive or iLUC (2015/1513) introduces a cap of 7% on the contribution of biofuels produced from 'food' crops used toward the transport goals in 2020 (also called 1st generation), putting a greater emphasis on the production of advanced biofuels (from waste, residue, non-food cellulosic or lignocellulosic biomass). National laws must be introduced in national legislation by 2017 together with the measures helping to reach the targets for advanced biofuels (an indicative target or 0.5% is given as reference). It also strengthens the minimum reduction threshold of greenhouse gas (GHG) emission applying to biofuels and bioliquids produced in new installations (these are explained in details in the present report under 4.1.2).

Fuel Quality Directive [EU, 2012]

The FQD requires from fuel suppliers that they gradually reduce specific fuel GHG emissions by 6% by 2020 compared to 2010, based on a life cycle analysis of GHG emissions per unit of energy (article 7a)[1]. Member States may choose to expand this reduction up to 10%. They may also choose to set the intermediate targets of 2% by 2014 and 4 % by 2017. The directive introduces also sustainability criteria to be fulfilled by biofuels while calculating GHG emission savings. These criteria rule out biofuels originating from the following: primary forest, protected areas, highly biodiverse grassland and raw materials with high carbon stock or peatland.
The emissions are calculated as follow:

$$FQD = \frac{Fossil\ transport\ fuels\ GHG\ intensity\ 2010 - All\ transport\ fuels\ GHG\ intensity\ 2020}{Fossil\ transport\ fuels\ GHG\ intensity\ 2010}$$

GHG intensity includes fuels used in road vehicles, non-road mobile machinery, rail, agricultural and forestry tractors and recreational craft.

Directive on the deployment of alternative fuels infrastructure (2014/94/EU)

The DAFI directive (2014/94/EU) aims at enabling an EU-wide harmonised strategy to boost the share of alternative fuels in the current fuel mix, dominated by petrol and diesel, through the development of the required infrastructure. It relies both on the involvement of Member States and the facilitation through the Commission. Nevertheless it does not define specific goals to achieve. It is conceived as a backup to reach the overall EU environmental goals. The directive aims at deploying an "appropriate number" of charging or refuelling points for CNG, LNG, hydrogen and electricity by 2020 - to be calculated based on the number of the vehicles expected to be on the roads.

The non-road sector is not directly affected by the DAFI requirements, since only a small share of equipment (mainly agricultural tractors and few construction machinery) is using public roads and those do not use public refuelling stations. However, developments for the road sector may lead to improvements in technology and cost reductions which NRMM can profit from.

Effort Sharing Decision

The Effort Sharing Decision establishes binding annual GHG targets for Member States for the period 2013–2020. These targets concern emissions from sectors not included in the EU ETS, such as transport (except aviation and international maritime shipping), buildings, agriculture and waste[2]. By 2020, the national targets should deliver a reduction of around 10% in total EU GHG emissions from the sectors covered compared with 2005 levels. Together with a 21% cut in emissions covered by the EU ETS, this will accomplish the overall

[1] According to the Directive: "It should amount to at least 6% by 31 December 2020, compared to the EU-average level of life cycle GHG emissions per unit of energy from fossil fuels in 2010, obtained through the use of biofuels, alternative fuels and reductions in flaring and venting at production sites".
[2] https://ec.europa.eu/clima/policies/effort/index_en.htm

emission reduction goal of the climate and energy package, namely a 20% cut below 1990 levels by 2020. A proposal for an Effort Sharing Regulation 2021-2030 was presented in mid-2016, it is the follow-up of the previous decision. The goal of reducing GHG emissions by 30% for non-ETS sectors in comparison with 2005 is shared between Member States.

3.2 National and regional policies in the agricultural sector

On the national level, the use of biofuels in the agricultural sector is generally supported by the German Energy Tax Act by an almost complete refund of the energy tax (leading to a final energy tax of only 2 ct/l). The resulting advantage, however, is considerably reduced by the fact that a general partial refund of the energy tax for diesel fuels used in the agricultural sector is also granted (the final tax amounts to 25.56 ct/l instead of 47 ct/l for road diesel) as shown in Table 3. Therefore, according to [KTBL, 2013], there is currently no competitive advantage for the regenerative fuels biodiesel and rapeseed oil / vegetable oil fuel.

Table 3: Diesel taxation in Germany

	Fossil diesel (road)	Fossil diesel (agriculture)	Biodiesel (agriculture)
Refund ct / l	NA	21.48	45.03
Energy tax ct / l	47.04	25.56	2.01

(Energy Tax Act §57 [Bundesregierung, 2017])

Several further incentives are given on the federal level (Bundesländer). Most notably the program RapsTrak200 of the Bavarian Ministry for Economic Affairs provides funding for using plant oils in order to increase the use of rapeseed oil and plant oil fuels in modern agricultural, forestry tractors and mobile working machines. Funding is available for:

- New acquisitions of tractors and mobile working machines of the exhaust stages IIIB (until 31.03.2016) and IV (until 31.12.2017), which are standardized for operation with rapeseed oil fuel
- Retrofitting of tractors and mobile working machines of the exhaust stages IIIB (until 31.03.2016) and IV (until 31.12.2017) for operation with rapeseed oil by authorized workshops

This partial financing is provided through non-repayable grants (promotion of projects). The subsidy rate is 80% of the eligible expenditure, but capped to 7,500 € per measure. If public investments or subsidies are granted from the federal or state government for the same funding purpose, funding under this Directive is excluded.

The state government of North Rhine-Westphalia (Nordrhein-Westfalen) is promoting a pilot project for the use of domestic vegetable oils in agricultural machinery. The aim is the demonstration of the full suitability of the tractors, the significant reduction in greenhouse gases and the contribution to domestic protein supply i.e. milk and meat production [NRW, 2015].

3.3 National and regional policies in the construction sector

While national policies for the agricultural sector focus on the use of alternative fuels, national and regional measures for the construction sector focus on pollutant emissions and target the use of after treatment systems and the early introduction of clean emission standards. Since construction machinery in Germany is subject to the European emission regulation the emission standards provide a categorisation of the emission level.

While the emission regulation at European level only regulates the approval of new engines, national measures are often also targeting the reduction of emissions in the machinery stock, e.g. by retrofitting.

The air pollution control ordinance in Switzerland is a model for obligatory use of "diesel particle filters" (DPF). Since 2010, new construction machines >18 kW had to comply with a particle number limit of $1 * 10^{12}$ at all construction sites, which requires the use of a particle filter. Older machinery of ≥37 kW has to be equipped with particle filter systems compliant with the air pollution control ordinance.

In Germany until 2013 only machinery in tunnel and underground construction had to be equipped with particle filters (refer to the "Technical Rules for Hazardous Substances" - TRGS 554 and TRGS 900). In the last few years, however, individual players have increasingly been using "clean" machines on construction sites. Examples are urban construction sites of the German Railway (Deutsche Bahn) and the large-scale construction site "Stuttgart 21". Now some municipalities and federal states have also moved on and introduced further local requirements for construction machinery in urban areas.

Construction machinery used in the context of municipal tenders of the **City of Berlin** (Berlin Senate) need to comply with at least the following emission standards of the Directive 97/68 / EC

- ≥ 19 to < 37 kW: Stage III A (or diesel particle filter)
- ≥ 37 kW: Stage III B (or diesel particle filter)

Construction machinery purchased by the Berlin Senate need to be equipped with a particle filter and comply with at least Stage IIIA ≥ 19 to < 37 kW), Stage III B (≥ 37 kW to < 56 kW) and Stage IV (≥ 56 kW).

Similar requirements for construction machinery have been introduced by the **City of Bremen** and became effective in 2016.

On the level of federal states, **Baden-Württemberg** has adopted an air quality ordinance for construction machinery for selected municipalities (currently Ludwigsburg, Reutlingen, Tübingen, Markgröningen and Stuttgart), which specifies first requirements from 2017 which are successively tightened:

- ≥ 19 to < 37 kW: Stage III A (or particle filter) until 2018, particle filter required from 2019
- ≥ 37 to < 56 kW: Stage III B (or particle filter) from 2017
- ≥ 56 kW: Stage III B (or particle filter) until 6/2017, from 7/2017 Stage IV (or particle filter)

Similar policies on the state level are currently being discussed in Bayern (Bavaria) and Niedersachsen (Lower Saxony). An overview of examples of Germany air quality policies applying to of examples for construction machinery on different levels is summarised in Table 4.

Table 4: Examples for construction machinery air quality policies in Germany beyond European legislation

Level	Measure	Scope
National	Use of particle filters	Tunnel and underground construction
Federal state	Compliance with latest emission stage or use of particle filter	Selected municipalities in the State of Baden-Württemberg
Municipal	Compliance with IIIB (III A ≥ 19 to < 37 kW) or use of particle filter	Berlin, Bremen
Company/Project	Use of latest emission stage or use of particle filter	Tenders for urban construction

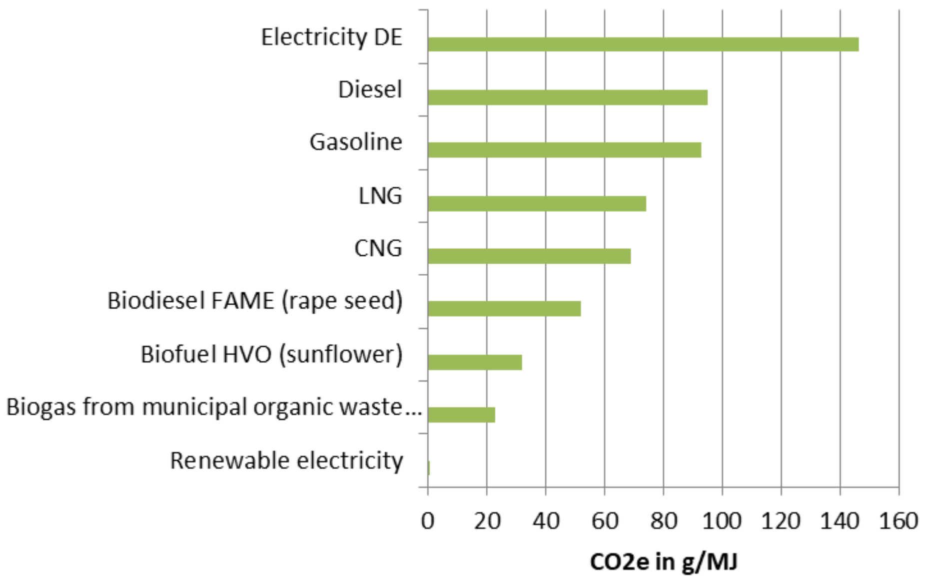
While policies for construction equipment aim at reducing air pollutant emissions, the regulatory framework has been giving lower priority to the reduction of GHG emissions and the use of renewable energies. However, air quality issues can also trigger a shift towards alternative fuels and renewable energy. Indeed, currently forbidding combustion vehicles is discussed in several countries e.g. France, the Netherlands, Norway, in order to foster the so called zero-emission vehicles, e.g. electric-cars. In the past, emission regulations for road vehicles, e.g. emission standards for new vehicles, or restrictions for using old engines in urban areas, have been later on also applied to NRMM.

4 Opportunities for using renewable fuels in non-road mobile machinery

The main renewable fuel alternatives, which are analysed for mobile machinery are:

- Biodiesel (either in blend or as pure biofuels)
- Pure vegetable oil (PVO) e.g. rapeseed oil
- Electricity
- Biomethane (pure or as blends to natural gas)

The main drivers for the use of renewable fuels are mostly climate protection considerations. Figure 5 presents the WTW GHG emissions of different fuels based on energy content (CO_2 eq/MJ). The lowest emissions have renewable electricity e.g. from solar or wind power, bio methane, followed by biodiesel. But GHG emissions vary largely according to the primary energy source used: while the production of electricity from renewable sources (e.g. wind or solar power) enables the reduction of WTW emissions to zero, the actual electricity mix in most European countries still relies on fossil fuels. Electricity in Germany is therefore associated with higher GHG emissions than petroleum products per unit of energy.



Source: 2009/30/EC, (EU) 2015/652, Destatis for German electricity mix (2016),
Figure 5: GHG emission of different fuels according to EU directives (well-to-wheel)

It has to be noted, however, that energy conversion in electric motors is by a factor 2-4 times more efficient than in combustion engines. Thus, even with the current German electricity mix electric motors can result in GHG savings compared to diesel or gasoline. Furthermore, they are by far more efficient in using renewable electricity produced from wind, water or solar power than hydrogen or Power-to-liquid solutions.

In principle there are also other technologies and fuels using renewable energy sources, which were not considered in detail in this study. Hydrogen, for instance, has been discussed for several years but has not been implemented due to the high price of fuel cells. The technology is therefore only in the prototype phase: a modern hydrogen fuel cell-powered tractor has been developed by New Holland. Their NH2 working prototype (79 kW) has independent electric motors for traction (NIL). Nevertheless the technical and economic potential is not mature enough. For other alternative fuels such as LPG, renewable options are currently limited. Similarly, power-to-liquid technologies which offer the option to produce synthetic drop-in fuels from renewable power in the future are yet in a test phase. These fuels are therefore not presented in the following sections.

4.1 Biodiesel

This chapter focuses on biodiesel as there is very low potential for ethanol within the NRMM sector due to the limited market penetration of spark ignition engines.

4.1.1 Market penetration potential

Biodiesel can be used in various blends. The limitation is linked to the overall availability, depending on the international demand for biomass, the compatibility of the fuels with the existing fleet and market prices.

Available diesel blends

Various technical options exist to use **biofuels as blends** in conventional diesel vehicles. They are nevertheless not always compatible with all models. B7 (biodiesel blend 7% v/v) can be used by all vehicles (incl. non road mobile machinery). Depending on the producer, higher blends can be used, for example John Deere allows concentration of 20% in volume for their tractors). It is also used in the construction sector, for example the Iowa-based Manatt's Inc, a road construction company using all types of engine e.g. pavers, trimmers, excavators have been using biodiesel blends between 2 and 20% (lower blends in winter) for years. Also, CAT has several biodiesel capable vehicles such as the 329EL hydraulic excavator (up to B20).

Hydrotreated vegetable oil (HVO) is seen by [Kadijk, et al., 2014] as a good option for mobile machines, where the limited amount of fuel required and the possible emission reduction compared to the current fleet could be noticeable. In this case any blend can be used form 1% to 30% without any compatibility issue. The limit would be the availability of the fuel. In 2015 the road sector consumed 299,198 t of HVO biodiesel against 1,895,750 t of FAME with a major part based on rapeseed (also UCO, palm oil and soy) in Germany [Zeddies, / Schönbler, 2016]. Currently, the installed HVO capacity in Europe reaches 2 million tons [The energy and water agency, 2015].

Currently **B100** is not common for mobile machinery nevertheless several models explicitly allow for the use of pure biodiesel. The quality of biodiesel is important and it must fulfil norm DIN EN 14214. [VDB, et al., 2014] provide a list of machines and engines with B100 approval including manufactures Caterpillar, Zeppelin, Liebherr, Deutz, etc. An example is the Caterpillar type 3064 hydraulic excavator. Most diesel engines approved for B100 fulfil the older emission standards EU II, IIIA or IIIB. However, for engines from stage IV onwards which rely on SCR and DPF, B100 still is in a test phase, e.g. in a recent research project by the University of Rostock (FNR funding number: 22012113). In agriculture and forestry industries the number of tractors registered as being able to run on B100 has been decreasing as a consequence of the low biodiesel demand [KTBL/TFZ, 2013]. According to [Zeddies, / Schönbler, 2016] 1,727 t of B100 was consumed in agriculture and forestry in 2015.

Table 5: Consumption of biofuels in Germany in the road sector in 2015

	FAME (total)	B100	HVO	PVO (rapeseed oil)
Agriculture and Forestry	n.a.	1,727 t	n.a.	n.a.
Total (transport)	1,895,750 t	3,454 t	299,198 t	1,970 t

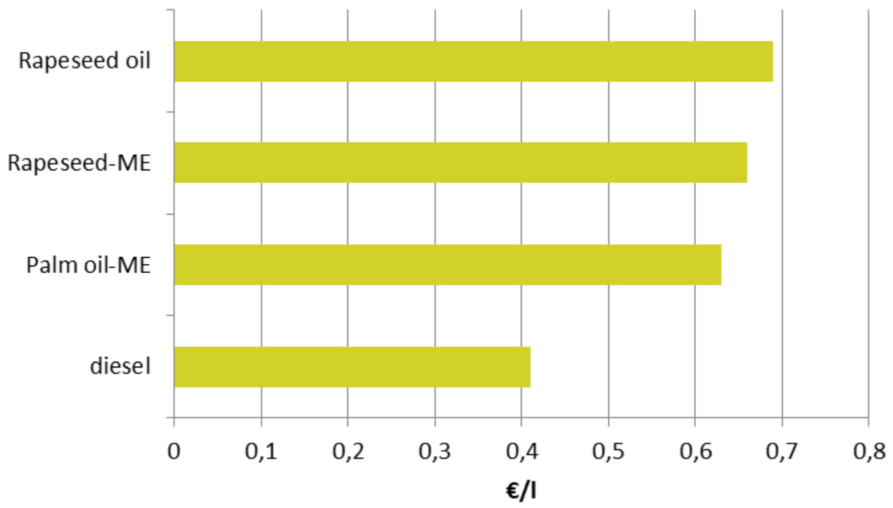
Source: [Zeddies, / Schönbler, 2016]

Infrastructure

Concerning the infrastructure there are no constraints for drop in fuels such as B7. However if higher blends are used, the area-wide availability of the corresponding pumps cannot be ensured, especially for agricultural machinery. This will depend on the investment of national and local governments. An alternative is a private supply for very large premises. A lesson can be learned from the past energy tax policy: the energy tax exemptions for biodiesel and plant oil in Germany triggered a boost in private refuelling infrastructure investments, but when the exemption was ended the market practically broke down. Therefore, market interventions should take into account the long-term perspectives. Looking at the RED II recast, the importance of biofuels might decrease after 2020 if 2nd and 3rd generation fuels do not become available and economically competitive (see next section).

Biofuel price

Figure 6 shows the prices of different fuels in Germany (without subsidies). The price for pure FAME from rapeseed or palm oil was about 50% higher than for diesel (January to July 2015). Several taxes are added to the market price, namely: energy tax and VAT, leading to a total price of app. 115ct/l.



ME: Methylester. Source: [Zeddies, / Schönbler, 2016]
Figure 6: Price of the fuels in Germany without subsidies between January and July 2015.

To reduce the retail price of biofuels for consumers, energy taxation can be reduced as for B100 until 2012. This tax reduction for B100 was phased out and B100 is currently taxed at the same level as diesel (per litre). Based on its lower energy content (32,7 MJ/l for FAME vs. 35,6 MJ/l for diesel) and the higher purchase prices this gives a clear disadvantage for biodiesel, which led to a strong decrease in the number of refuelling stations.

Table 6: Current energy tax for Diesel and B100 in Germany, related vehicles and infrastructure

Fuel	Fuel tax	Vehicles	Refuelling stations
Diesel	0.47 €/l	~15 million diesel cars, many trucks busses…	~10,000
B100 (FAME)	0.185 €/l until 2009, 0.17 €/l 2009-2012, then 0.45 €/l	Trucks and agriculture tractors, cars	~1,900 in 2007, ~250 in 2009

Source: German energy tax law, KBA statistic and internal studies from the authors

There is almost no demand for biodiesel in the agricultural and forestry sector [KTBL/TFZ, 2013], even though full biofuels e.g. B100 are still untaxed for these sectors (see 3.2). But as fossil fuels are also partially exempted of taxes, biofuels are still not advantageous.

4.1.2 Environmental sustainability

Biofuels need to comply with several sustainability criteria to be credited towards renewable energy and fuel quality targets. The main environmental criteria according for the RED and the iLUC directive (Indirect Land Use Change, EU 2015/1513) are:

- Achieving GHG savings of at least 35% in comparison to fossil fuels (standard value: 98g CO_2e/MJ). This saving requirements (based on a life cycle analysis) rise to 50% in 2017 and 60% in 2018, but only for new production plants (in RED II it raises to 70% in 2030) – showed in Figure 7.
- Setting a cap of 7% on the contribution of biofuels produced from 'food' crops to the goal of 10% RES in transportation (adding to the fact that biofuels from non-crop sources count twice) and the indicative target for advanced biofuels is 0.5%.
- Securing that biofuels are not stemming from areas converted from land with previously high carbon stock such as wetlands or forests or from raw materials obtained from land with high biodiversity such as primary forests or highly biodiverse grasslands.

The current draft of the RED II (giving objectives for 2030) plans to set a share of:

- Minimum 6.8% from advanced biofuels and biogas produced from feedstock listed in Annex IX
- Minimum 3.6% from advanced biofuels and biogas produced from feedstock listed in Part A Annex IX
- 1.7% cap on Annex IX Part B feedstocks, including UCO

These decisions are driven by current concerns on biofuels produced from food crops actually having negative environmental impact. A central point is that the land required to grow crops used for biodiesel is detrimental for the environment and does not compensate for the lower GHG emissions of vehicles running on biofuel. Moreover biofuels have been blamed to be responsible for price spikes on the world food markets, but data to quantify this effect are divergent. This may then lead to a rising demand for biofuels of the 2nd generation and in the future 3rd generation, whose availability is currently limited.

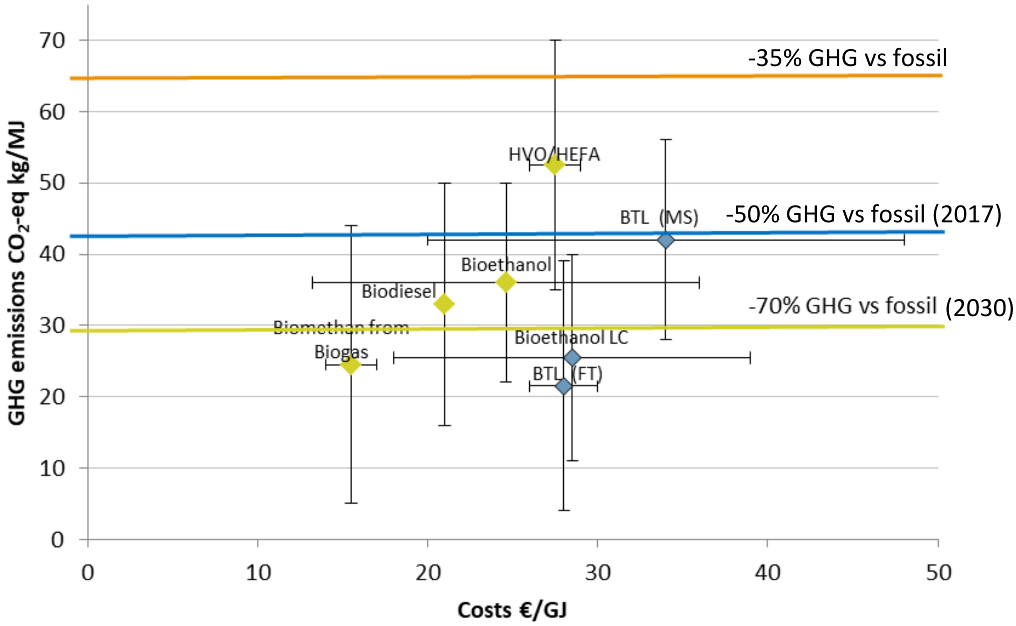
Table 7: List of the different generation of biodiesel

Biofuels	Defined by feedstock	Defined by technology maturity
1st generation	Vegetable oil Animal, waste oil	Fermentation Etherification Esterification
2nd generation	Biomass to liquid Hydrogenated oil FAME from non edible seeds e.g. jatropha New seeds oil e.g. cotton seed	Gasification/synthesis Hydrotreating Hydrogenation Lignocellulose process
3rd generation	Biodiesel from algae	Pyrolisis Hydrothermal upgrade

Source: [Concawe, et al., 2010]

The environmental impact of different biodiesels vary significantly as shown in Figure 7, comparing the GHG emissions of different biofuels to their production costs. The green dots are biofuels, which are commercially available, while blue dots depict biofuels, which need to be further developed before being mature to enter the market. The emissions of the most widespread biofuels i.e. biodiesel and bioethanol depend on their feedstock e.g.

produced from UCO (app. 16 g CO_2-eq/MJ) or from wheat (around 50 g CO_2-eq/MJ). The FAME are the most used, but the less environmentally friendly. HVO shows a similar pattern: it can be mixed until 30% v/v with diesel but it is currently expensive and mainly produced out of crops. The future technologies such as biofuel from ligno-cellulose (LC Ethanol) and BTL (biomass to liquid) have higher emission savings but are still expensive or not mature. Biogas has a good potential as a cheap fuel and with limited emissions (when produced out of waste) – for more details see 4.4.



Source: ifeu & [DLR, et al., 2014]; Nominal prices are given as indication, they refer to different years (2010 to 2015)
Figure 7: THG emissions and costs of different biofuels

The emissions shown above do not take into account the iLUC emissions (also not considered for the moment in the FQD), which means that the real emissions may be higher. According to ifeu calculations it could more than double the global impact, for example FAME (fatty acid methyl ester) from palm oil could jump from approximately 39.5 g CO_2-eq/MJ to 109 g CO_{2eq}/MJ (with iLUC emissions), which would exceed the emissions of fossil fuels amounting to 98 g CO_2-eq/MJ.

4.2 Pure vegetable oil (PVO)

4.2.1 Market penetration potential

PVO has already been used for years as fuel for mobile machinery, especially in the agricultural sector. The main challenges are the engine adaptation, fuel quality control and emissions control (e.g. PM emissions under cold start). The current consumption of rapeseed oil in the transport sector amounts to 1,970 t in 2015 [Zeddies, / Schönbler, 2016].

In the past retrofit solutions were available to meet the emission standards I, II and IIIA and bivalent solutions exist such as tractors from Fendt or Deutz-Fahr (start with normal diesel and continuous operation with plant oil). Similar to B100 a major challenge is the adaptation to EU Stage IV for non-road vehicles. According to the field tests of the 2ndVegOil project (based on a total of 24,000 operating hours of 16 tractors) and monitoring program (run in Germany, France, Austria and Poland) diverse plant oils can be used as fuel if the 2nd generation quality is ensured (2G-PPO) [The 2ndVegOil consortium, 2012]. Based on the decreasing attractiveness of PVO (increasing fuel prices), the demand for compatible vehicles is currently low and it is not incentivising vehicle producers to speed up the penetration of compatible tractors of the last generation in the market.

The production of PVO can be locally done by farmers and is the best option, as the fuel is particularly advantageous for the agricultural sector. The price of rapeseed oil in Germany is not competitive with the conventional fuels, RME[1] price notation in 2014 and 2015 oscillated between 700 €/t and 830 €/t, always slightly higher than FAME [Zeddies, / Schönbler, 2016]. Generally the number of refuelling stations offering PVO is very limited and it is not expected to increase.

4.2.2 Environmental sustainability

The benefits of pure plant oils are due to their chemical properties and by their way of production, involving few process steps. They can also be produced economically in small production units with only small energy losses (no thermal or chemical process) and short transport distances, while other biofuels show higher energy losses. The non-toxicity and low flammability are also two non-negligible advantages. It can also be a source of additional income for farmers. Generally their sustainability is similar to biofuels and depends on the feedstock and the quality of the fuel. The 2ndVegOil project found that the GHG savings could go up to 60% for tractors running on 2G-PPO from rapeseed. The quality of the fuel is highly influenced by the seed growing conditions and by the oil pressing process. It was shown that the content of phosphorous (P), calcium (Ca) and magnesium (Mg) played a major role in the trouble-free operation of advanced engines [The 2ndVegOil consortium, 2012].

Until now, the main crop used for PVO was rapeseed, its ecological advantages are limited (no biological production possible and limited production level), therefore several crops were tested in the context of the 2ndVegOil project, including false flax, maize germs, jatropha oil and sunflower. An in-situ oil cleaning methods was developed allowing the use of the oil cake as animal feed, practicable in small agricultural enterprises. A European standardization Committee (CEN) Workshop Agreement defined minimum requirements of two classes SVO with and without exhaust gas after-treatment systems (CWA 16379) [The 2ndVegOil consortium, 2012]. In parallel two other German norms exist: the DIN 51605 for rapeseed oil and DIN SPEC 51623 for plant based fuel.

[1] Rapeseed methyl ester

4.3 Electricity

4.3.1 Market penetration potential

In general, electric machinery is not very common for mobile machinery and traditionally more often used in stationary applications. However, there is also a trend to increase electrification. There are different possibilities for using electricity in NRMM, e.g.:

- Electrification of auxiliary equipment
- Hybrid electric machinery using diesel generators
- Full electric machinery connected to the power grid by an electric cable.
- Full electric machinery using batteries

Agriculture

Several solutions exist to electrify auxiliary equipment. One example is to replace the actuator (present in e.g. tractors to harvesters, sprayers, spreaders or seed drills). Tractor accessories that can be electrically powered include the engine cooling fan, the air brake compressor, the air conditioner compressor, the engine water pump, and hydraulic pumps One example is the Belarus 3023 tractor's electro-mechanical drivetrain, with a 300-hp engine powering and a 220-kW generator, which is claimed to have fuel consumption reduction of 15 to 20%. Optional equipment includes an electric cooling fan for the radiator, an electromechanical front PTO shaft that can operate at speeds independent of engine speed, and an autonomous electric power station for 172.5 kW of auxiliary power. Several other models are still in the prototype stage. AGCO has developed a prototype, electrically powered, high-clearance sprayer that is claimed to deliver 35% more power to the ground than its conventional counterpart with the same engine [Roger, et al., 2014]

Fully electric agricultural machines have been a key research area under the SESAM project. The aim is to allow the use of decentral and renewable electricity from renewable sources. The concepts developed for agriculture aims at demonstrating the economic efficiency of electric mobility. One noticeable advantage is that farmers do not need a nationwide charging infrastructure since the machines are charged at the farmyard. Furthermore, the e- tractors can be used as both stationary and mobile buffers of the energy produced at the farm itself [Federal Ministry for Economic Affairs and Energy, 2015]. An example for full electric tractor is the John Deere SEASAM concept with a 130 kWh battery.

Construction

According to [Clausen, et al., 2016] the construction sector is one of the most important early adopter of electric vehicles (representing 12% of the EV users) – contrary to agriculture, forestry and fishing industries (only 2.5% of the users) in Germany. Typical construction equipment which can be electrified by connection to the grid includes e.g. tower cranes or compressors. Smaller equipment e.g. saws or vibrating tampers can be electrified both by grid connection or batteries. Stationary excavators e.g. for scrap yards can be relatively easily electrified by grid connection, but represent a rather small share of NRMM applications.

For the bigger mobile earth moving and loading equipment which account for the largest energy consumption of the NRMM sector, electrification is still in a test and market entry phase. Currently several models ranging from auxiliary electrification, hybrid to full electric drive trains are starting to be available or being developed. Volvo Construction Equipment presented the new HX2 autonomous, battery-electric, load carrier. The second-generation concept machine is part of an electric site research project that aims at electrifying a transport stage in a quarry – from excavation to primary crushing and transport to secondary crushing. It involves developing new machines, work methods and site management systems – and reducing carbon emissions by up to 95% and total cost of ownership by up to 25%. Some examples from the US market are described in Table 8.

Table 8: Example of electric incl. hybrid or electric accessories vehicles in the construction sector on the American market

Vehicle	Drive train	Energy savings
John Deere electric wheeled loader	Hybrid	-25%
Caterpillar's crawler dozer D7E	diesel with electric accessories	-10 to 30%
Komatsu's excavator H205-1	Hybrid	-25 to 41%
Ricardo hybrid excavator demonstrator	flywheel energy storage system	-10 to 30%
Caterpillar's hydraulic excavator 336E H	Hybrid	- 25%
Volvo electric hybrid wheel loader LX1	Hybrid	- 50%
Volvo autonomous, load carrier HX2	Battery electric	n.a.

Source: [Roger, et al., 2014] & Volvo

The advantage of these vehicles is that they are cycling machines, meaning segments of their typical work cycle involve dissipation of kinetic energy during e.g. direction changes or braking/deceleration, they are therefore well suited to be hybridised and equipped with energy recovery systems. This is not the case for many agricultural activities such as tillage or planting.

Another main advantage of full electric machinery - especially for indoor applications - is air pollutant emission reduction. A most common example is battery electric fork lifts which are available from several big manufacturers including Hyster, Toyota, Still, Linde, CESAP and others. Recent examples for construction machinery are the micro excavator Wacker Neuson 803 dual power or wheel loaders Wacker Neuson WL20e and Kramer 5055e.

Charging infrastructure

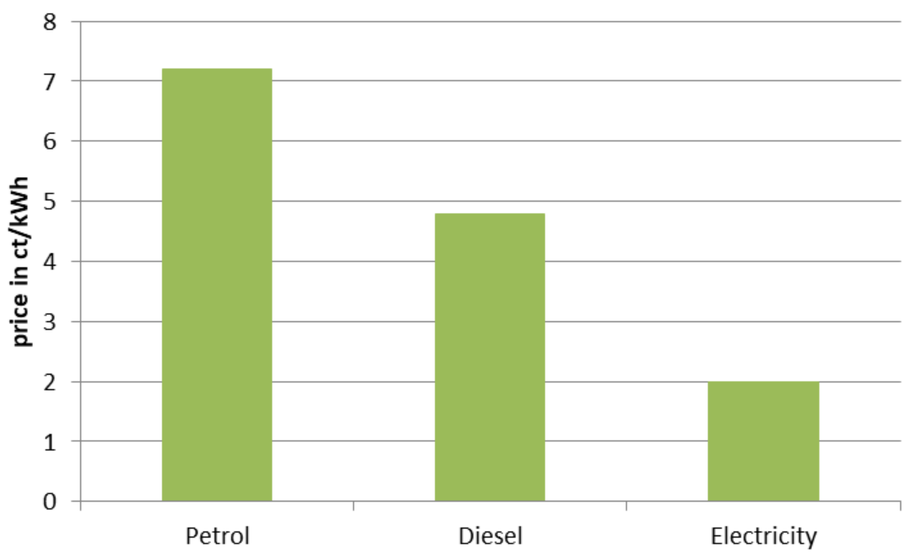
Electricity is in general available for most industrial sectors that have connection to the power grid. The availability of renewable electricity increased subsequently in recent years and is assumed to become the most important carrier for renewable energies in the future (see the chapter on sustainability).

In most cases power plugs are designed for stationary equipment and are not suitable for most mobile machinery parks. Also, in case of more flexible battery powered applications charging times can take several hours without special designated charging infrastructure.

Recent activities for public charging stations, including fast charging points focus on road transport. As of the end of 2015, some 5,836 recharging points for electric vehicles were available in Germany. North Rhine Westphalia and Baden Württemberg are running ahead of the other German Länder [BMWi, 2016]. Nevertheless e-infrastructure is generally concentrated in urban areas. This may mean that using electricity as fuel in the agricultural sector requires developing e-infrastructure in the countryside or developing private charging points.

Costs of electricity

Since 1999 electricity is taxed according to the "Stromsteuergesetz" (StromStG) in Germany (including the electricity used for charging e-cars). The energy tax amounts to 2,05 ct/kWh, which is largely below petrol taxes (defined in the "Energiesteuergesetz"): 7,3ct/kWh and diesel 4,7 ct/kWh as shown in Figure 8. For all energy sources the VAT is added on top of these taxes. The compulsory levy for petroleum products amounts to 0,46ct/l for petrol and 0,39 ct/l for diesel. Though this tax does not apply to electricity, other special taxes do, such as the Renewable Energy Sources Act levy (EEG Umlage) - the most important one as it represents a share of 40% of the total levies on electricity-

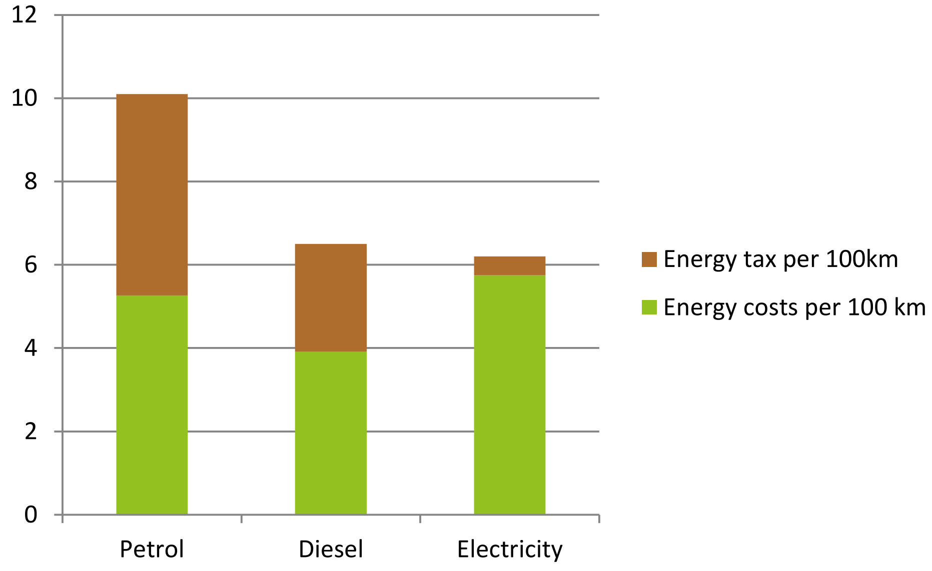


Sources: [ADAC, 2016] and [BDEW, 2015]
Figure 8: Energy taxes for petrol, diesel and electricity in Germany in 2015

In order to compare energy prices, the efficiency of the vehicles, normalised per kilometre, must be taken into account. To allow a fair comparison, prices are based on private cars as energy prices vary according to the various sectors (tax reduction exist for the agricultural sector that are not applied to the construction sector) and the various technologies are not well represented in the mobile machinery fleet. According to TREMOD fuel consumption data[1], the price of using a petrol medium car is around 10€ per 100 km, while a diesel car would cost slightly more than 6 € and an e-car only slightly less as shown in Figure 9. Assuming that the differences in energy efficiency are similar for NRMM, electricity has more or less similar energy costs than diesel equipment. The picture might change if diesel gets

[1] TREMOD "Transport Emission Model" is calculation software for transport emissions in German, developed by ifeu for the German Federal Environmental Agency.

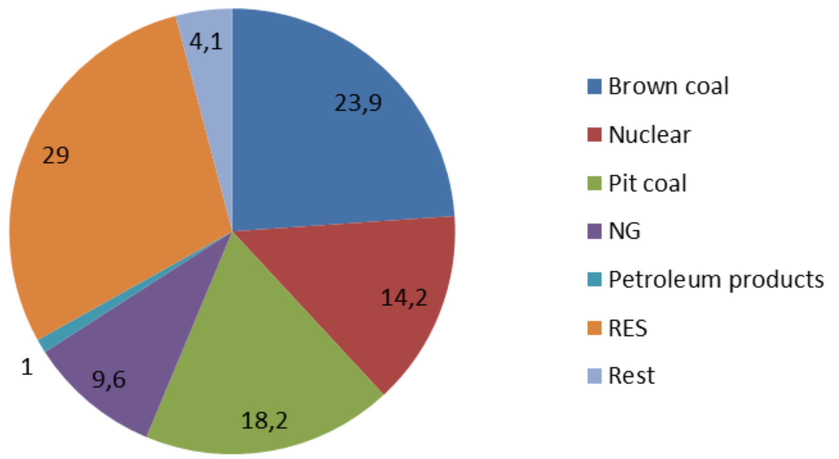
more expensive. For example, [ifeu, 2017] concluded that the current tax reduction for diesel must be cancelled if the consequences of the Paris Agreement on Climate change are being taken seriously. Moreover official price forecasts such as from the World Energy Outlook by the IEA assume significant oil price increases in the future [International Energy Agency, 2013].



Energy consumption based on TREMOD (Petrol: 7.4l/100km; Diesel 5.5l/100km; electric: 21.9 kWh/100 km)
Figure 9: Energy costs for different private car technologies in 2015

4.3.2 Environmental sustainability

Figure 10 shows that the German electricity mix in 2015 reaches almost 30 % of renewable energy sources (RES). Nevertheless still 41% of the electricity is produced from coal with clear negative impacts on average GHG emission (see Figure 10). The production of 1 MJ of electricity in Germany leads to 146 g of GHG emissions i.e. 527 g/kWh in 2016 [UBA, 2017], which is slightly higher than the average in the EU value of 145 g. Nevertheless the share of renewable electricity sources in the average mix is expected to increase in the future. The BMWi plans in its NREAP to achieve a minimum of 35% of RES in the electricity mix, up to 40% in the efficiency scenario [BMWi, 2015]. Furthermore individual efforts (e.g. photo-voltaic installations on farm buildings) for additional renewable electricity could further improve the GHG balance.



Source: [Destatis, 2017a]
Figure 10: German electricity mix in 2015 (%)

4.4 NG/Biomethane

Another option for using biomass in transport is biomethane, which requires similar refuelling[1] and vehicle technology than natural gas. Due to its chemical similarity to fossil methane biomethane can be combusted in NG engines at a very high ratio [KTBL/TFZ, 2013]. For some vehicles LNG can be used instead of CNG but must be maintained at low temperature, a process than can be carried out only for vehicles than can be constantly driven i.e. not very suitable for mobile machinery.

4.4.1 Market penetration potential

Two options exist for using natural gas in tractors for diesel replacement:

- pure natural gas
- dual fuel systems: typically split between 80 to 90% natural gas and 10 to 20% diesel, with diesel used primarily during ignition

Some tractors have been developed by the firms Valtra and Steyr and are in a test-phase. Both system rely on mixing biomethane and diesel (the Valtra tractor can achieve a maximum share of biomethane of 83%). Nevertheless due to the lower energy density of methane and the limited capacity of the gas tanks (because of the size and the weight) the current gas tanks have a capacity of around 170l so that the range of the vehicle is quite limited (especially for agricultural work having high energy demand such as tillage) [KTBL/TFZ, 2013]. For example The Profi 4135 of Steyr would have an estimated operation

[1] Besides refuelling station technology, an infrastructure for biomethane distribution is required, e.g. it can be a profitable business for small scale producers it if they can inject their biomethane production in an existing gas grid.

time of 49% of the one expected for an equivalent diesel tractor and it would use 1.7 times the volume for CNG compared to diesel [Roger, et al., 2014]. New Holland created a 135-hp methane-powered research tractor that can also run on diesel fuel. This tractor is being tested in Europe where on-farm production of biogas is available. The T6.140 Methane Power tractor can store 50 kg of compressed gas, which provides fuel for approximately half a workday, but can be supplemented with diesel fuel from a 15-L diesel tank [Roger, et al., 2014].

The number of natural gas refuelling stations in Germany amounts to around 900, which ensures a good geographical coverage but it is focused on urban centres and cities. The availability for the agricultural sector may therefore be limited. Overall 31,436 t of bio-methane have been consumed by the road sector in 2015 in Germany.

Gas prices (mainly coming from Russia, Norway and the Netherlands) have been decreasing in the last years: from 3.8 ct/kWh in the second half of 2013 to 2,64 ct/kWh in the second half of 2016 for industries [Destatis, 2017b]. Costs for biomethane are composed of production costs, processing of biogas into biomethane and transport/infrastructure costs. In Germany the costs of injecting biogas ("Wälzungskosten") in the gas network has been decreasing too: from 2.9 in 2011 to 2.1 ct/kWh in 2015 [Bundesnetzagentur, 2016]. The German parliament approved the new energy and electricity tax acts in June 2017, which confirmed tax reduction for CNG and LNG until 2026, progressively decreasing from 2024 on [EUWID, 2017] as shown in Table 9. For heavy duty trucks, the fuel cost savings of CNG vehicles can lead to a payback of higher vehicle prices in less than 3 years [DLR, et al., 2015]. In general, methane powered equipment could gain increasing importance for the NRMM market, if manufacturers of NRMM further invest in this technology.

Table 9: Natural gas tax, vehicles and infrastructure

Fuel	Fuel tax	Vehicles	Refuelling sta-
CNG/LNG/BioCH4	0.18 €/kg until 2023, and then continuous increase until 0.4 €/kg in 2027	~ 100,000 cars, few busses and trucks	~900

4.4.2 Environmental sustainability

GHG emissions savings (WTW) from biomethane can be higher than for other biofuels (compare Figure 7), but depend on the type of feedstocks (GHG emission reduction of 73 to 82% according to the EU-RED). Currently natural gas incorporates 20% of biomethane [EUWID, 2017]. Fossil natural used as CNG has also lower GHG emissions than conventional diesel (around ~27% lower in terms for g CO2e per MJ according to the [European Parliament and of the Council, 2015]). However, studies for heavy duty vehicles show that based on operational indicator (e.g. g CO2e per km) GHG-savings can be lower, because spark ignited gas engines are less efficient than diesel engines [DLR, et al., 2015].

5 Conclusions

Mobile machinery makes a significant contribution to the total transport emissions in Germany. Reducing these emissions is therefore of high importance, also in the light of climate protection goals. Therefore several renewable fuel alternatives have been analysed for mobile machinery, namely biodiesel (blend or pure biofuel/vegetable oil), electricity and biomethane. A comparative assessment of these options is graphically summarised in Figure 11 along the lines of technical compatibility, environmental sustainability and energy costs. For each criterion a ranking between 0 (worst among the compared options) and 2 (best among the compared options) has been undertaken.

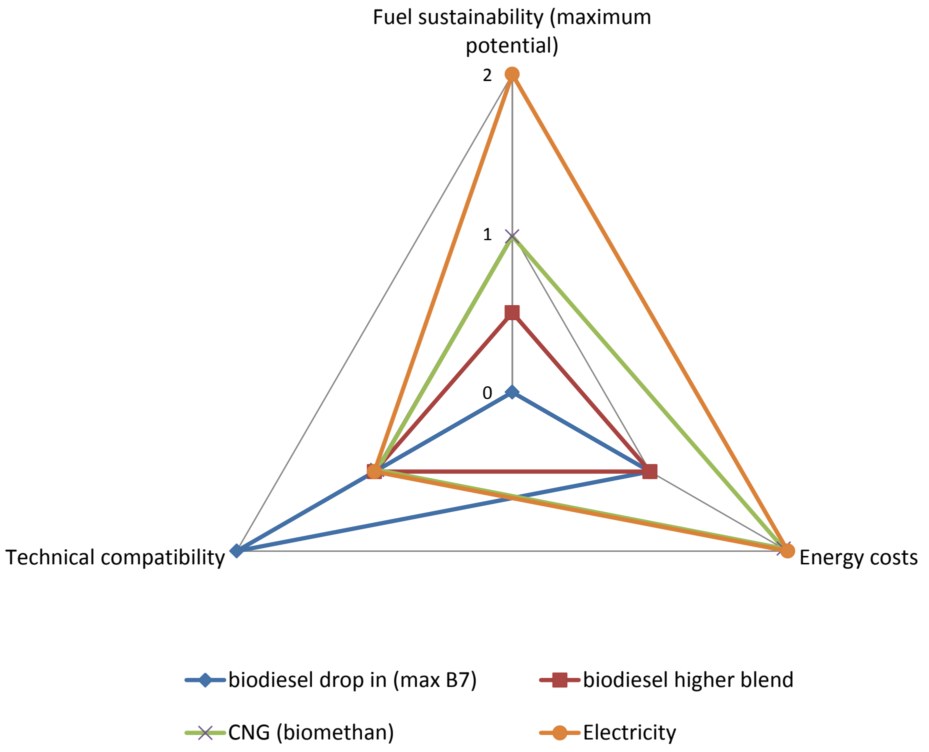


Figure 11: Indicative ranking of the main renewable fuels for mobile machinery (0=worst; 2=best)

Biodiesel (B7) can be seen as a low hanging fruit in terms of technical compatibility because it relies on a very good infrastructure (available in all fuel stations) and a perfect compatibility to all existing diesel vehicles. On the other hand side such lower blend has a limited environmental impact, offering a maximum potential of 370 Million litres of biofuel use out of over 5 billion litres of diesel consumed by NRMM in 2015.

Higher blends of biodiesel (for example B20 and at the highest level B100 or its oil equivalent: PVO) can bring considerable additional emission savings, depending on the feedstock. For example biodiesel from used cooking oil emits only 14g CO_2e/MJ against 93g CO_2e/MJ for diesel[1], a reduction of 85%. Nevertheless the infrastructure availability for high blends is very limited, so that using this kind of oil or biodiesel requires a local production (for example PVO for agriculture) or private pumps.

At the other end of the spectrum is electricity, having the highest environmental potential (if renewable electricity is used). It also ranks very well in terms of energy costs. The main obstacles are the currently growing but still limited e-vehicle market penetration and the limited infrastructure, especially in rural areas.

Finally CNG with a high share of biomethane is a possible alternative to petroleum products, but the environmental impact varies much according to the share of biomethane and feedstock used. Biomethane availability is also limited and the public infrastructure relies still heavily on fossil gas. In case of on-site production, feeding bio methane into the grid (similar to renewable power) would be a feasible alternative if a de-centralised production of CNG is too expensive. First models of gas powered machinery are being produced and tested.

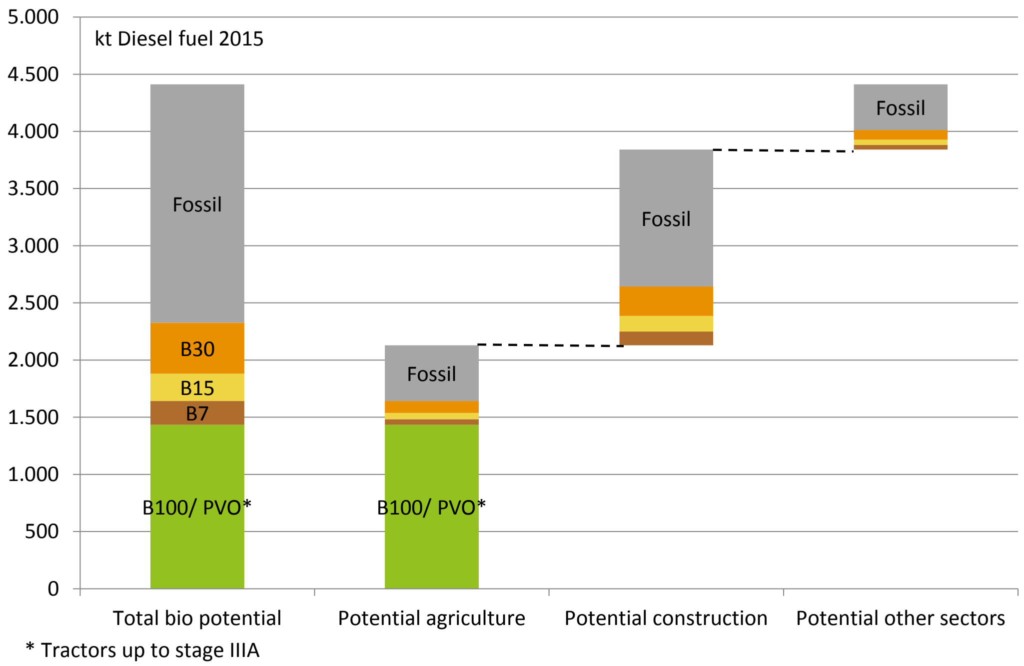


Figure 12: Maximum potential scenario for using biofuels in mobile machinery

Figure 12 illustrates an estimation of the maximum potential resulting from the exploitation of biofuels in the field of mobile machinery based on the diesel consumption in 2015 according to TREMOD-MM. It assumes that all tractors up to stage IIIA would use B100 or PVO. The other sectors would rely on biodiesel blends: B7, B15 or B30. In total about 2,300 kt of diesel fuel could be substituted by biofuels which is more than 50 % of the total diesel consumption of mobile machinery. The agricultural sector clearly makes the largest contribution due to the assumed high potential for use of B100 or PVO. In practice, however, only a small share of this potential is likely to be realised in the near future due to issues of compatibility of the fuels with current vehicles, infrastructure availability, local production facilities and energy costs, as described in the previous chapters.

[1] Source: http://www.biograce.net/

TREMOD-MM Methodology and Input Data

Methodology and coverage

TREMOD-MM is based on the "population method" (Tier 3 model) and uses highly differentiated input data

TREMOD MM basically uses the so-called "population method" (Tier 3 method) to calculate fuel consumption and exhaust emissions of several pollutants of combustion engines in non-road equipment and machinery in Germany from 1980 until now and in scenarios until 2030. This methodology is internationally established for the calculation of emissions from mobile machinery. A similar approach is used in Switzerland, the United States (EPA NON-ROAD model) and other European states (COPERT).

Emissions are calculated via vehicle stock, activity and emission factors:

$$E_E = Num \times P \times O \times LF \times EF$$

with

E_E	Exhaust emissions (of one layer, e.g. emissions from agricultural tractors, model year 2010 with 37-75 kW in 2015)
Num	Number/Stock of machinery/devices/vehicles
P	Average Power (of this layer)
O	Average operational hours
LF	Typical load factor (<1)
EF	Emission factor (g/kWh)

An example for the differentiation of the machinery is shown in Figure 13.

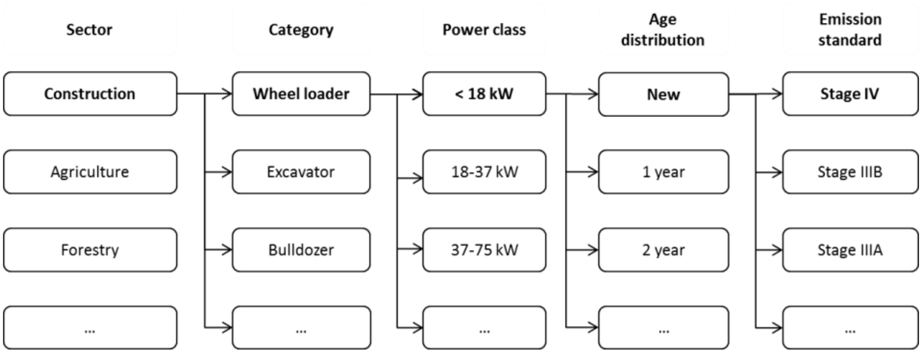


Figure 13: Differentiation of machinery in TREMOD MM

The emission factors consider transient behaviour and aging of machinery; furthermore evaporative and refuelling emissions are calculated

Emission data until stage IIIA have mostly been available for the standardized stationary cycles (for the definition of cycles see ISO standard 8178) for new engines. To adapt these emission data to the real behaviour, adjustment factors for the aging behaviour (deterioration factor = DF) and dynamic behaviour (transient adjustment factor = TAF) are used in TREMOD MM:

$$TAF\,[-] = \frac{Emission_{transient}\ in\ \frac{g}{kWh}}{Emission_{stationary}\ in\ \frac{g}{kWh}}$$

Furthermore, evaporative and refuelling emissions are considered. Thus total emissions are calculated as follows:

$$E_T = E_E + EV + E_R$$

with:

E_T: Total emissions

E_E: Direct exhaust pipe emissions

E_V: Evaporative emissions (only hydrocarbon)

E_R: Refuelling emissions (only hydrocarbon)

The coverage of TREMOD MM is documented in Table 10. A total of 47 types of machinery are considered, of which 21 belong to the construction sector. Since private and professional use of household / gardening equipment are treated as different machine types, in this sector, 12 types of machinery can be found. In contrast, the forestry sector comprises 5 and agriculture only 4 types of machinery. For industry and others only generator sets and forklifts are considered.

Table 10: Coverage of TREMOD-MM

Pollutants	Sectors	Power classes	Fuel/Engine types
BC (Black Carbon)	Agriculture	< 18 kW	Diesel
CH4	Forestry	18-36 kW	Gasoline 2-Stroke
CO	Construction	37-74 kW	Gasoline 4-Stroke
CO_2	Industry / Generators	75-129 kW	LPG
FC (Fuel Consumption)	Household / Gardening	130-299 kW	
HC	Recreational Boats	300-560 kW	
N2O			
NH3			
NMHC (Non Methane)			
NOx			
PM (Particulate Mass)			
PN (Particulate Number)			
SO_2			

Input data

The differentiated calculation approach of TREMOD MM requires a large number of detailed input data. These are derived on the basis of various sources (see Table 11) and are extensively documented in [ifeu, 2004a] [ifeu, 2009] and [ifeu, 2014a]. This section therefore only provides an overview of the most important data sources with a particular focus on the agricultural and construction sector.

The data quality varies between the sectors. In the case of vehicle stock data, detailed statistics are only available for agricultural tractors from the Federal Motor Transport Authority (Kraftfahrtbundesamt = KBA). The remaining vehicle stock data is either obtained from association statistics (e.g. forestry) or calculated, based on sales numbers (e.g. construction and industry, household / gardening). Regarding the use of the equipment (annual operating hours), various machinery resale platforms have been evaluated as well as industry data analysed. These were then compared to literature data from similar models.

The basic emission factors are not machinery specific but depend on the fuel type, power class and emission standards of the engines. In the case of diesel engines up to stage II, extensive data were evaluated (see [ifeu, 2004b]; For gasoline engines up to stage I), which were additionally compared to literature values from other countries. From stage IIIA onwards (for petrol engines from stage I), an estimation of the emission factor based on the emission limit value and expert judgement was carried out.

Table 11: Overview of data sources for TREMOD MM

Sector	Stock	Operation hours	Emission factors
Agriculture	Data from the Federal Motor Transport Authority for tractors	Literature values and data from machinery resale platforms	Cross-sector factor depending on power class and engine type: Diesel engines: Up to stage II measurement data and literature values Stage IIIA-IV based on expert judgement and emission limit values Gasoline engines (2-/ 4-stroke, Gas): Up to stage I measurement data and literature values For stage I-II emission limit values and EPA certification data
Forestry	Data from the Board for Forestry and Forestry Technology (KWF)	Literature values and data from machinery resale platforms	
Construction	Until 1996 official statistics (Federal Statistical Office); afterwards data from market studies; Size and age categories according to industry data and resale platforms	Literature values; data from machinery resale platforms; Industry data	
Industry/Other	Sales numbers; production statistics; Industry data	Literature values; data from machinery resale platforms; Industry data	
Households / Gardening	Sales numbers	Literature and industry data	

Main input data for agriculture

In the agricultural sector mainly diesel-driven tractors and combine harvesters are used as motorized machines. The forestry tractors used exclusively in forestry are considered in the "forestry" sector. The power bandwidth of machinery is large, ranging from very small field tractors with a power <18 kW to large tractors and combine harvesters with more than 130 kW.

The German Federal Motor Transport Authority (KBA) regularly collects vehicle stock data for tractors, which are differentiated by registration year and power class. The TREMOD-MM inventory is based on these data.

Retrofitted tractors, which are registered in the KBA statistics under tractors, are often used in forestry. The share is, however, very small with less than 1 % of the total stock. Nevertheless forestry tractors are subtracted from KBA's stock data for the agricultural sector and considered in forestry.

Data on the stock of combine harvesters are based on data from the Federal Statistical Office up to 1994, which have been updated in line with the existing model for tractors on the basis of new arrivals [BLE, 2008]. For 2014, the vehicle stock is estimated at more than 60,000 combine harvesters.

The operating hours were determined by means of an elaborate procedure by evaluating machinery resale platforms. Data are also differentiated according to power classes, showing that machines of a higher power class are used significantly more than low-power engines. Load factors are mostly based on the data of the Swiss 'Bundesamt für Umwelt' [BAFU, 2008].

Main input data for construction

In the construction industry, machines are used in road construction and civil engineering, and vary greatly in size and performance, depending on the application area. Most of these are diesel-operated and only a few electric, gasoline or gas-powered machines are used. Trucks used in the construction industry, within the TREMOD structure, are taken into account in the road transport sector. Cranes, pumps, welding equipment and cooling units have for the most part an electric drive and therefore do not contribute to air pollution emissions. Generators and forklifts are considered in the industrial / other sector.

Data on the construction machines are based on data from the statistical yearbooks of the FRG (or the GDR) until 1996, the further inventory development up to 2010 is based on the population numbers published by the British consulting company "Off Highway Research" on individual device types [Off-Highway Research, 2011] and the development of the production and foreign trade statistics of the Federal Statistical Office [DESTATIS, 2011], where the vehicle stock development between 1996 and 2010 was modelled based on the production figures and import/export. Since no comprehensive inventory statistics after 2010 are available, a conservative extrapolation of the past trends was adopted.

An extensive evaluation of current empirical sources (see [ifeu, 2014a]) was used to determine the annual operating hours as most of the larger construction machines have operating hour counters. Data for this evaluation have been deducted from a machinery resale platform [GB, 2011] and from companies. For the machinery resale platform, care was taken to include only machine for sale in 'Germany'. A sample of over 10,000 machines has been analysed.

However, the average annual operating hours recorded are only mean values for 2011. In order to adjust the utilization intensity to cyclical fluctuations, the annual operating hours are corrected by reference years. For this purpose, a price-adjusted index of the turnover in underground construction is used, which is based on data from the Federal Statistical Office and the main association of the German construction industry. This index fluctuated by about 30 % over the last twenty years, and has fallen since the mid-1990s. Since an increase in the number of machines took place in most categories during the same period, an adaptation of the utilization was considered to be plausible in order to reflect the economic development.

The shares of vehicle stock on the different power classes and the average performance per class are also based on company data [ifeu, 2014a].

Input data for other sectors

In addition to classical timber management, forestry also includes the afforestation and maintenance of the forest as well as the maintenance of paths and other tasks. The machines used for this purpose are hand-held motor or chain saws and large forestry machines for harvesting timber. Smaller work such as transport and maintenance in the forest are usually carried out by tugs. The data situation has been improved by a machine survey carried out by the Board for Forestry and Forestry Technology (KWF). This survey is based on sales figures. Large machines in forestry are exclusively diesel-powered and have small stocks; additionally there are a large number of hand-held power saws with Otto engine.

The operating hours and load factors are based on data for Switzerland [BAFU, 2008]. In this case, a correlation is also made with the wood production, similar to the construction industry.

In the household and gardening sector, mainly gasoline- and electric-powered appliances are used. Lawn mowers, ride-on mowers, motor saws, trimmers and other equipment are considered. These devices generally have lower operating hours than the devices in other categories. However there is a high amount of devices. Furthermore, there are also many professionally used devices with significantly higher operating hours. Therefore professional and private use of the same machine types are distinguished as separate device categories.

The machine stock in the household and gardening sector is mainly derived from sales figures and estimated life span of the devices, and aligned with European inventory statistics [JRC, 2008]. The operating hours and load factors are once again based on data for Switzerland [BAFU, 2008].

In the industry / other sector, generators and forklifts mostly use diesel fuel, some forklifts also use LPG. The stock was estimated on the basis of industry data. In the absence of further information, the inventory of generators sets was modelled solely on the production figures, as well as the import, export and scrapping rate of the devices.

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