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An emissions inventory for non-road mobile machinery (NRMM) in Switzerland

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Abstract

Non-road mobile machinery (NRMM) contributes a significant part of the total energy consumption and air pollutant emissions of mobile sources. The latest update of the Swiss non-road emissions inventory (FOEN 2015) quantifies energy and fuel consumption as well as regulated and four non-regulated pollutants for the period 1980-2050. Emissions are calculated using a bottom-up model in which operating hours segmented by machine type, motor type, size classes with respective nominal power, and age are multiplied with load factors. The resulting energy demand is multiplied with fuel consumption and emission factors.
While energy consumption of NRMM has increased by 5% between 2000 and 2015, the emissions of most air pollutants are decreasing due to the introduction of stricter emission limits. Agricultural and construction machines are the largest sources of NO_x and PM emissions; regarding CO and HC emissions, garden-care appliances are more relevant than construction machinery, however. The share of the non-road sector in total mobile energy consumption has slightly increased to 9% in 2015. The share in air pollutant emissions is even higher due to the time lag in emission standards. The transition from combustion engines towards electric motors is in progress, mainly in the industrial and residential sectors.

Keywords: Non-road mobile machinery, inventory, modelling, emission control, electric devices.

1 Introduction

Non-road mobile machinery (NRMM) is the term used for all mobile machines and devices that are not intended to transport passengers and goods by road. It

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includes construction machines like excavators, load and dump trucks, mobile industrial, commercial, and municipal appliances like forklifts, snow groomers or street cleaners, agricultural and forestry machines like tractors, harvesters, chain-saws, garden-care appliances like lawn-mowers, boats and ships, rail vehicles, and military machines like tanks. Aircraft are usually not considered part of NRMM. In terms of fuel type, larger mobile machines are mostly diesel-powered, while smaller machines and hand-held devices mostly have spark-ignited two- or four-stroke petrol engines. However, CNG and LPG are also used (mostly for forklifts), and increasingly, electric motors are used to power smaller devices.

NRMM contributes a significant part of the total energy consumption and air pollutant emissions of mobile sources. While its share in total mobile energy consumption in Switzerland remains below 10%, NRMM emits roughly 20% to 40% of the regulated pollutants, depending on the reference year (FOEN 2008, FOEN 2015). The larger share in air pollutant emissions is due to the fact that for many years, the non-road sector was a neglected area of air pollution control. In the EU, the first emission limits for NRMM entered into force in 1999 (TE 2015).

Switzerland compiled its first non-road emissions inventory in 1996 (FOEFL 1996). It has been updated twice since, in 2008 and 2015 (FOEN 2008, FOEN 2015). In this paper, the methodology and key results of the latest update are presented.

2 Objectives

The main objective of the research presented here is the update of the Swiss non-road emissions inventory in order to meet Switzerland's reporting duties towards the international conventions UNFCCC (UN Framework Convention in Climate Change) and CLRTAP (Convention on Long-Range Transboundary Air Pollution). This includes the update of all activity data, load factors, emission factors, and correction factors, as well as the review of all underlying assumptions. The inventory reports energy and fuel consumption and direct emissions of the following machine categories:

- Construction machinery;
- Industrial machinery (also including commercial/public works machinery);
- Agricultural machinery;
- Forestry machinery;
- Garden-care and hobby appliances;
- Ships and boats;
- Diesel rail vehicles;

- Military machinery.

The current update implements several improvements with respect to previous versions. First, in order to improve the comprehensiveness of the inventory, the list of included machinery is complemented by a few machine types neglected so far:

- Generators in industry, commerce and public administration (so far, only generators in construction and the military had been included);
- Vehicles and mobile machinery of the airside sector of airports;
- Inland barges on the Rhine River.

Second, machines and appliances with electric motors are newly included due to the fact that mainly for small, hand-held devices, electric versions are becoming increasingly popular due to improvements in battery technology. Since the primary aim of this inclusion is the monitoring of the transition from combustion engines to electric motors, only machine types that are traditionally part of NRMM inventories are included; consequently, electric railway transport is excluded, as well as hand-held devices for indoor use that never operated with combustion engines. Since the inventory focuses on direct emissions, only energy consumption but no (indirect) air pollutant emissions from electric devices are reported.

Third, in addition to fuel consumption, CO_2 and the four regulated pollutants carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM) included in the previous inventory, the four non-regulated pollutants methane (CH_4), non-methane hydrocarbons (NMHC), benzene (C6H6) and nitrous oxide (N_2O) are included. For PM, only exhaust emissions are considered.

Fourth, since Switzerland has implemented strict particle filter requirements for machinery operated on construction sites through its Ordinance on Air Pollution Control (OAPC), the impacts of this legislation are assessed, as well as the impacts of the current and future emission standards on diesel particle filter (DPF) use.

Fifth, the modelled period (starting in 1980) is extended to 2050 instead of 2020; this implies taking into account longer-term economic forecasts, and most importantly, the Euro-V emission standard.

Sixth and last, the impact of delayed implementation of emission standards due to the sell-off periods and the flexibility scheme provided for in the EU Directive 97/68/EC is assessed.

3 Methodology

General approach

The Swiss non-road emission model implements a bottom-up approach in which operating hours segmented by machine type, motor type, size classes with respective nominal power, and age are multiplied with load factors. The resulting energy demand is multiplied with fuel consumption and emission factors, and corrected with four correction factors:

$$Em = N \cdot H \cdot P \cdot \lambda \cdot \varepsilon \cdot CF_1 \cdot CF_2 \cdot CF_3 \cdot CF_4 \qquad (1)$$

Where:

Em = emission per machine type, pollutant, emission standard (in grams or tonnes p.a.)

N = Stock [number of machines/devices]

H = annual hours of operation [h/a]

P = mean nominal capacity [kW]

λ = effective load factor (dimensionless)

ε = emission (or fuel consumption) factor [g/kWh]

CF_1 = correction factor for the deviation of effective load from the standard load in the cycle on which the emission factor is based (dimensionless)

CF_2 = correction factor for dynamic utilisation of the machine (dimensionless)

CF_3 = correction factor for deterioration of the machine (dimensionless)

CF_4 = correction factor for diesel particle filter (DPF) use (dimensionless)

The calculation methodology outlined above refers to fuel consumption and the four regulated pollutants CO, HC, NO_x and PM.

By contrast, CO_2 emissions directly depend on fuel consumption. The fuel-based emission factors in the non-road model (corresponding to the results presented here) are differentiated by fuel type but constant (published in FOEN 2015); for climate reporting from 2015, CO_2 emissions were recalculated using temporally varying CO_2 emission factors (published in FOEN 2016; the deviations to the results presented here are minimal).

Emissions of non-regulated air pollutants are calculated as follows: Components of hydrocarbons (CH_4, NMHC, benzene) are calculated as shares of HC differentiated by type of fuel and engine technology. For benzene, an additional differentiation is made between the periods before and after 2000, since in that year the limit level of 1% for benzene content entered into force. For N_2O, emission factors in g/kWh differentiated by engine technology, are applied (see also FOEN 2015).

Activity data

Inputs on stock, and operating hours were collected from various sources. The approach differs between the periods 1980-2000, 2000-2015, and 2020-2050.

For the period 1980-2000, activity data from the previous non-road emissions inventory (FOEN 2008, stock and operating hours based on EWI 2005) were used in most cases. Stock or operating hours were only retrospectively adjusted if more recent information was available that made a correction necessary.

For the period 2000-2015, official or industry association statistics were used where available. These include the database of the Swiss Federal Motor Vehicle Inspection Office (MOFIS), the inventory data of the Swiss Master Builders Association (SBV 2013), the periodical agricultural census and the federal government's import/export statistics (Swiss-Impex, EZV 2014). Market studies (Off-Highway Research 2005, 2008, 2012) were another important source for the development of construction machinery and tractors. The applications for fuel tax refunds, as well as applications for the use of heating oil, submitted to the Federal Customs Administration, were evaluated. Questionnaires were mailed to manufacturers, importers and operators. To complement the information gathered from these sources, expert workshops were held to discuss the available information and make estimates to fill data gaps. Age distributions were in the majority of cases taken from EWI (2005) and adjusted in a few cases (mostly based on the MOFIS database).

The forecasts up to 2050 are based on various sources. For the construction and the industrial sectors, economic forecasts were available up to 2030 (VÖV 2012), and were extended up to 2050 by taking into account predicted population growth (medium scenario of the Federal Statistical Office, BFS 2014). For agricultural machines, the activity forecast is based on the forward projection of the historical trend in agricultural area. For military and railways, long-term planning information up to 2020-2030 was provided by the Army Logistics Basis (LBA), Swiss Federal Railways (SBB) and the Bern-Lötschberg-Simplon (BLS) railway; for the subsequent period, the trend was projected forward with gradual levelling-off. For the remaining sectors, the historical trends were projected forward, with a gradual level-off assumed from 2020.

Load factors were basically taken from the previous version of the emissions inventory (FOEN 2008), for which they had been mostly estimated by industry experts. For the 2015 update, they were reviewed during the expert workshops mentioned above, and adapted where necessary. For construction machines and their military equivalents, the load factors were adapted based on the findings of Fridell et al. (2014). For rail vehicles, and partially for large ships, fuel consumption values were available alongside operating hours and nominal power, so that load factors could be calculated from these inputs.

Emission factors

The emission factors for diesel machines not subject to emission regulation (Pre-Euro and small machines <18 kW) are based on EPA (2004) and measurements of black smoke carried out by the Swiss Federal Laboratories for Materials Testing and Research, Agroscope and IVECO (FOEN 2008).

For diesel machines and pollutants subject to the EU emission regulation, the emission factors are based on the respective limit values and the emissions from type approval tests. Where total limit levels from HC + NO_x apply, 90% of these were allocated to NO_x and 10% to HC (in accordance with IFEU 2009). In the case of EU-IIIA to EU-V for HC, and for EU-IIIA only for NO_x, 10%-30% were deducted from the limit value to derive the emission factors. For NO_x and PM from EU-IIIB to EU-V, the limit values are applied as emission factors without any deduction, since it is assumed that manufacturers can hardly keep emissions below these stringent emission limits. For CO, the emission factors amount to between 12% and 37% of the limit values based on type approval emissions.

For petrol-powered devices, the emission factors for the pre-Euro period are based on assumptions deduced from measurements in the framework of an alkylate gasoline study (INFRAS 2008). For the regulated period (Euro stages), the emission factors are derived from the limit values with a deduction of 10%.

The emission factors for ships and boats are largely based on the applicable limit values specified since 1995 in the SAV (Swiss Ordinance on Pollutant Emissions from Ship Motors) and the Euro stages from 2003. Emission limit values up to emission category EU-IIIA are adopted minus a tolerance of 10%; for the emission stage EU-V, the tolerance of 10% is only applied for HC and CO, and for NO_x and PM the emission limit levels are applied without deduction.

For rail vehicles, the emission factors for older machines correspond to the emission limit recommendations of the UIC and the factors for diesel machines with the same year of manufacture. The emission factors for post-2006 engines correspond to the EU limit values from EU-IIIA minus a tolerance of 10%. For Euro-V, the manufacturing tolerance of 10% is only applied for HC and CO.

The emission factors of gas-powered machines are based on measurements of engines with different degrees of retrofitting (without after-treatment, with oxidation catalysts, with 50% or 100% of machines with 3-way catalysts).

The emission factors of the non-regulated pollutants CH_4, NMHC, N_2O and C_6H_6 are taken from EEA (2013), IFEU (2009), and Mayer (2005). For CH_4 and NMHC, they are based on complimentary fractions of total HC.

The limit values for the planned EU-V emission standard are based on a draft presented at a 2014 GEME (EU expert group on emissions from Non-Road Mobile Machinery) Meeting (EC 2014); they have not been adapted since.

All emission and fuel consumption factors along with information on their sources can be found in the Annexes of FOEN (2015; see download URL under References).

Fuel and electricity consumption factors

Fuel consumption is calculated in the same way as emissions by applying fuel consumption factors in g/kWh instead of emission factors. The fuel consumption factors in the Swiss non-road emission model are based on the following sources: EPA 2004 (diesel machines), DLG 2008 (petrol devices), FOEFL 1996 (ships and boats), IFEU 2003 and data from locomotive manufacturers (rail vehicles). For diesel machines, the fuel consumption factors are differentiated by size class but constant in time, whereas for petrol engines, a development parallel to HC emissions is assumed.

For electricity consumption, the reciprocal value of the efficiency level is used instead of a consumption factor in g/kWh. The overall efficiency level is the product of the individual efficiency levels of the motor, the battery and the charger. Different assumptions apply for industrial NRMM and for garden-care/hobby appliances (based on Nipkow 1989, Dieterich 2012, TASPO 2013, Dolder 2014; for details see FOEN 2015). The resulting overall efficiencies are published in FOEN (2015).

Correction factors

The Swiss non-road emission model uses four types of correction factors (see above). All parameter values are published in FOEN (2015).

The *load correction factor* (CF_1 in formula 1 above) adjusts fuel consumption of diesel machines for the deviation of the actual engine load from the average engine load of the test cycle (Non-Road Steady Cycle NRSC, also referred to as ISO 8178-C1) that the fuel consumption factors are based on. It is calculated with the following formula:

$$CF_1 = 2.0095 - 2.1981 \cdot \Delta_{LF} + 1.1886 \cdot \Delta_{LF}^{\;2} \qquad (2)$$

Where:

CF_1 = load correction factor

ΔLF= ratio of effective load to standard load

The effect of the load correction factor is that the specific consumption at an effective load of e.g. 20% is around 30% higher than at the NRSC load factor of 48% (see Figure 1).

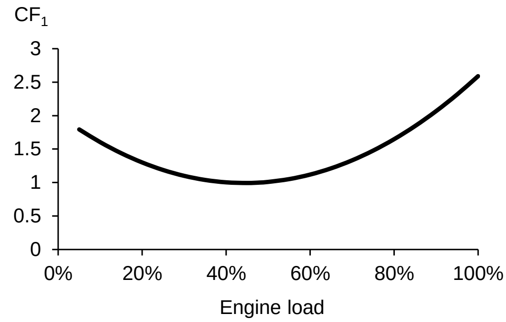

Figure 1. Relationship between engine load and load correction factor CF_1.

The *correction factor for dynamic use* (CF_2 in formula 1) corrects the emissions of the regulated pollutants due to dynamic machine use (i.e. frequently changing load, as opposed to the stationary load points of the NRSC). The values used for CF_2 up to EU-IIIA are based on EPA (2004). For EU-IIIB, CF_2 is set to 1.0 for all machine categories and pollutants. For EU-IV and EU-V, values greater than 1.0 are used for NO_x for all machines between 56 and 560 kW in order to account for the higher specific emissions at low engine loads due to the Selective Catalytic Reduction (SRC) only being activated at higher loads.

The *deterioration correction factor* (CF_3 in formula 1) corrects emissions for deterioration due to wear and tear. It is applied to all machines up to EU-IIIA after a given period of operation based on the age distribution of the machine park and the annual operating hours. From EU-IIIB, manufacturers have to prove the stability of emissions over extended operating periods (EC 1997), therefore CF_3 is set to 1.0 for newer machines.

The *diesel particle filter (DPF) correction factor* (CF_4 in formula 1) applies to all diesel machines equipped with particle filters (ex-works or retrofitted). It corrects PM emissions and fuel consumption for DPF use. Fuel consumption is increased by 3% for machines with DPF; the correction of PM emissions depends on the size class and the emission standard, since also machines without DPF have to meet the applicable limit values, and these differ between EU stages. The limit values of EU-IIIB and EU-IV can be met with either DPF or other after-treatment technologies (Integer 2013), but PM emissions are lower with DPF. For the regulated power range of EU-V engines, it is expected that DPFs will be necessary to meet the emission limits (especially the PN emission limit), therefore the DPF correction factor is set to 1.0.

The share of machines equipped with DPF was estimated separately by machine family and area of operation.

For construction machinery >18 kW operating on construction sites, the Swiss Ordinance on Air Pollution Control (OAPC) prescribes the use of a DPF from 2010, with a grace period for machines >37 up to 2015. For the emission model, it is assumed that this law is implemented (which in fact seems to be the case based on sample inspections).

For diesel machinery operating outside construction sites, the shares of machinery equipped with DPF up to 2010 are based on sales of DPF systems, data cited in the consultation procedure on the revision of the SAV (Swiss Ordinance on Pollutant Emissions from Ship Motors), and information provided by railway operators (SBB 2012, BLS 2012) and the Army Logistics Basis (LBA). For the period 2010-2020, DPF use was estimated based on the emission reduction strategies of machine manufacturers for stages EU-IIIB and EU-IV (Integer 2013; see Table 1), the respective marked shares of these manufacturers in Switzerland (Off-Highway Research 2008, 2012), and the turnover of the machine park depending on the life expectancy by machine category and size class.

Table 1. Planned installation of diesel particle filters (DPF) in engines >18 kW in emission stages EU-IIIB and EU-IV, by manufacturer ("partially" indicates that in tendency, higher-powered engines are fitted with DPF).

Manufacturer	**Stage EU-IIIB / US Tier 4 Interim**	**Stage EU-IV / US Tier 4 Final**
AGCO	No	No
Caterpillar	Partially	Yes
CNH	No	No
Cummins	Partially	Partially
Deutz	Partially	Yes
IHI	No	No
Isuzu	Partially	No
John Deere	Partially	Yes
Komatsu	Partially	Partially
Kubota	Partially	Yes
Liebherr	Partially	No
Takeuchi	No	No
Volvo CE	Partially	Not yet known
Volvo Penta	No	No
Weichai	No	No

4 Results and discussion

Activity and emissions in 2015

In 2015, almost three million machines and devices defined as NRMM were active in Switzerland. In total, they were operating for approximately 290 million hours and consumed 17.9 PJ of energy (Table 2). This amounts to 9% of the total mobile energy consumption (road transport plus NRMM) in Switzerland (Table 4).

Most energy is consumed by large machines in construction (35% of the total), agriculture (28%), and industry (19%). The bulk of the stock (81%) and operating hours (61%), however, is attributed to garden-care appliances, which only account for 3% of the total energy consumption of NRMM. This discrepancy is due to the fact that in garden-care, a large number of small devices with low power (mostly <4 kW) is owned by private households, most of which are operated for short periods only every year. The reason why garden-care appliances account for such a large share of operating hours lies primarily with the lawn robots that operate more or less continuously during the entire vegetation period – however, with minimal energy use (around 25 W).

Diesel is the fuel most used for NRMM with 83%, followed by petrol with about 10%. Electricity already accounts for 5% of non-road mobile energy consumption, while gas and light fuel oil (LFO, used by some passenger ships) account for about 1% each.

Table 2: Stock, operating hours, and energy consumption by machine category in 2015.

Category	No. of machines	Operating hours per machine [h/a]	Total operating hours [million h/a]	Energy consumption [PJ]
Construction machinery	58'900	420	24.8	6.2
Industrial machinery	69'700	680	47.2	3.4
Agricultural machinery	313'600	100	31.5	5.1
Forestry machinery	11'300	190	2.2	0.4
Garden-care/hobby appliances	2'417'200	70	177.1	0.5
Ships and boats	96'400	40	3.4	1.6
Diesel rail vehicles	640	720	0.5	0.4
Military machinery	13'000	70	1.0	0.3
TOTAL	2'981'000	100	287.6	17.9

The absolute emission levels of regulated pollutants and CO_2 in 2015 are presented in Table 3. In total, about 1.25 million tons of CO_2, 7600 t of NO_x and 360 t of PM were emitted in 2015. The share of NRMM in total mobile air pollutant emissions is greater than its share in energy consumption, due to the time lag in emission regulations regarding NRMM compared to road transport: depending on the pollutant, the share of NRMM is between 18% and 33% in 2015. For the greenhouse gas CO_2, the share of NRMM only amounts to 8% - slightly less than its share in energy consumption due to the electric machines that do not emit CO_2 directly (Table 4).

Greenhouse gases are dominated by CO_2, which accounts for 98.6% of total CO_2eq in 2015 (CH_4: 2'900 t CO_2eq or 0.2%, N_2O: 15'200 t CO_2eq or 1.2%). The share of biogenic CO_2 is minimal with 1.1%.

Table 3: Emissions of regulated air pollutants and CO_2 by machine category in 2015.

Category	**Carbon monoxide (CO) [t/a]**	**Total hydro-carbons (HC) [t/a]**	**Nitrogen oxides (NO_x) [t/a]**	**Particu-late matter (PM) [t/a]**	**Carbon dioxide (CO_2) [t/a]**
Construction machinery	3'400	299	2'290	40	458'400
Industrial machinery	1'530	115	922	39	192'300
Agricultural machinery	13'500	1'060	2'520	226	374'300
Forestry machinery	1'580	167	129	8	28'700
Garden-care/hobby appliances	10'600	561	72	-	30'300
Ships and boats	4'320	462	1'110	39	114'500
Diesel rail vehicles	210	46	397	4	29'000
Military machinery	452	24	122	3	20'100
TOTAL	35'600	2'730	7'600	359	1'248'000

Depending on the pollutant, different machine categories are the largest sources among NRMM. Regarding CO_2, the ranking is identical to energy consumption (see above), with construction machinery emitting most of the greenhouse gas, followed by agricultural and industrial machinery.

Regarding NO_x, NRMM in agriculture (with 33% of emissions) surpasses construction machinery (30%) in 2015, followed by ships (15%) and industry (11%). With regard to PM emissions, agricultural machinery is by far the largest source accounting for 63% of emissions, leaving behind construction, industry and ships with 11% each. The reason why agriculture surpasses construction in terms of NO_x and PM emissions in spite of lower energy consumption is the longer lifespan of agricultural machines (mostly tractors) that slows down the pervasion of the machine park with new engines with more advanced emission technology. The even more relevant reason regarding PM is the fact that machinery on construction sites is subject to the stringent DPF requirements of the Swiss Ordinance on Air Pollution Control (OAPC), while there are no federal laws going beyond the Euro emission limits affecting agricultural machinery (see also paragraph on DPF use below). Also in terms of CO and total HC, agricultural machinery is the largest source (accounting for 38% and 39% of emissions, respectively). Here the primary reason is the high petrol use by single-axle mowers which have relatively high nominal power and are operated at high engine load. However, also the large number of small hand-held devices with 2- or 4-stroke petrol engines in agriculture, forestry, and garden-care make an important contribution towards CO and HC emissions, making garden-care the second-most important source of these pollutants (accounting for 30% and 21% of emissions, respectively).

With respect to the non-regulated pollutants, the emission shares per machine category for the hydrocarbon fractions methane, NMHC, and benzene are naturally similar to those of total HC. They vary slightly with fuel type and engine technology distributions among the machine categories, however. For example, garden-care appliances contribute more towards methane emissions than towards NMHC due to the dominance of 2-stroke engines that emit a higher share of methane (about 7% of total HC) than 4-stroke petrol engines (3.4%).

Table 4: Comparison of NRMM and road transport consumption and emissions in 2015.

	Non-road mobile machinery [t/a]	**Road transport [t/a]*)**	**Share of NRMM in total (road + non-road)**
Consumption			
Diesel	352'100	2'057'000	15%
Petrol	40'000	2'425'900	2%
Energy	17.9 PJ	183.8 PJ	9%
Emissions			
Carbon monoxide (CO)	35'600	90'800	28%
Hydrocarbons (HC)	2'730	12'580	18%
Nitrogen oxides (NO_x)	7'600	32'240	19%
Particulate matter (PM)	359	737	33%
Carbon dioxide (CO_2)	1'248'000	14'132'700	8%

*) Note that road transport refers to fuel used (territorial consumption) and not to fuel old.

Development of activity and emissions

While in the previous non-road emission inventory (FOEN 2008), a slight decline of total operating hours of NRMM was forecast after a peak around the years 2000-2005, the 2015 update shows that NRMM activity has significantly increased since then. Total energy consumption increased by 5% between 2000 and 2015. The most important driver of this development has been the growing construction sector, while in the other important non-road sectors, i.e. industry and agriculture, energy consumption has stagnated or even decreased. Regarding operating hours, the largest increase is observed with garden-care appliances, again due to the growing popularity of the lawn robots with their long operating hours but low energy consumption (see above).

The emission levels of almost all pollutants modelled for the Swiss non-road emissions inventory increased until the year 1995. Benzene emissions fell sharply with the introduction of the lower limit level for benzene in petrol in 2000. From 2002, i.e. the entry into force of the EU emission standards, emission levels of all pollutants (except the greenhouse gases carbon dioxide and nitrous oxide) began to decrease significantly. The sharpest decline can be observed with PM, the emissions of which have decreased by almost 70% between 2000 and 2015.

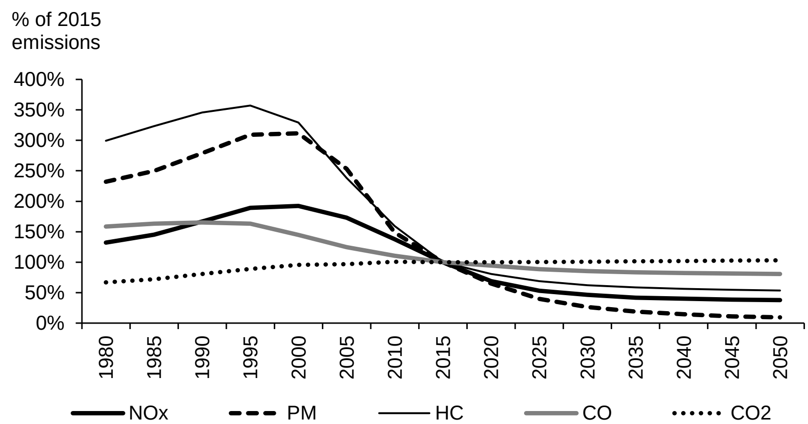

Figure 2. Development of the emissions of regulated air pollutants and CO_2 for the period 1980-2050, expressed in % of emissions in the year 2015.

In the future, a further reduction is expected for the majority of pollutants as a result of the pervasion of the machine park with newer engines with improved technology. The extent of this reduction remains to be verified, however, with emission measurements of EU-IIIB, -IV and –V machines (see section on uncertainty below). A further increase of emissions (though at a slower pace) is only anticipated for the greenhouse gases CO_2 and N_2O. The level of PM emissions is expected to fall most sharply: here a reduction to less than 10% of the 2015 level is anticipated by 2050. This reduction is attributable to cleaner engines in general, and to the anticipated use of diesel particle filters (DPF) with the EU-V emission standard in particular.

Currently and in the near future, however, DPF use differs widely between areas of application. As compliance with the EU stage IIIB and IV limits for PM can be achieved without the use of diesel particle filters (DPF), most manufacturers comply with these requirements by the use of SCR (mostly for larger machinery >56 kW) or EGR technologies (mostly for smaller machines <56 kW) (Integer 2013; see also Chapter 0). Only with the particle number (PN) limits of stage V (from 2019/2020), DPF application will is expected to become inevitable for all areas of application. So far, in Switzerland only machinery on construction sites is required to be equipped with DPF. Furthermore, the pervasion of the machine park with DPF depends on the life cycle of machinery, which is longer in agriculture than in the construction or industry sectors. Therefore, estimated DPF use in 2015 varies between 4% in agriculture and 73% in construction machinery (Figure 3). The share of construction machines equipped with DPF does not exceed the latter value due to the fact that on one hand, not all construction machines are actually used on construction sites (other applications like quarrying are not affected by the particle filter legislation), and on the other hand, a sizeable share of construction machines (e.g. mini excavators) is below 18 kW and therefore neither affected by the DPF legislation nor the EU directives. The impact of the Swiss particle filter legislation is still significant, however: In 2015, more than 130 t of PM emissions from construction machinery could be avoided, which is 77% of the amount that would have been emitted without the respective law.

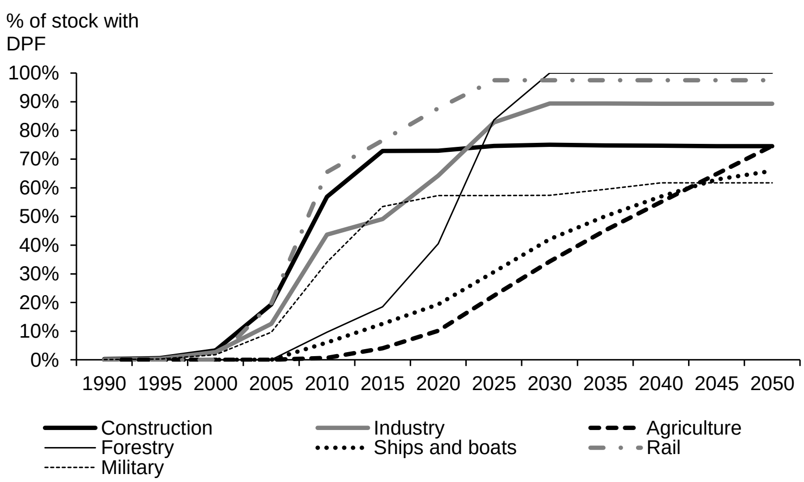

Figure 3. Percentage of machines equipped with diesel particle filters (DPF).

Sources of uncertainty

Emission calculations are always uncertain, and since the total emissions within a geographic region cannot be measured, benchmark figures on which to calibrate the total are lacking. Fuel sales, which are often used to calibrate fuel consumption in road transport emission models, cannot be used for NRMM in Switzerland, as only the total fuel sales for road and non-road are known (except for agriculture, for which there was a time-series on fuel consumption available up to 2004, from which the consumption in the present inventory only deviates by 1-2%). In the following paragraphs, the most relevant sources of uncertainty in the Swiss non-road emissions are discussed.

Regarding *activity data*, sources of uncertainty include the stock of machinery as well as the size class distribution, the respective operating hours and age distributions, the degree of diesel particle filter (DPF) use, and the delayed implementation of emission standards.

For larger machinery in construction and agriculture, stock, operating hours, size class and age distributions are rather well known from official data sources like the Swiss Federal Motor Vehicle registration database (MOFIS) or the agricultural census, or industry association statistics. The same is valid for large ships, rail vehicles and military machinery, for which there are a few large operators that can provide the necessary information. By contrast, for smaller machinery, especially hand-held devices, information is relatively scant and therefore a large degree of estimation is involved. The uncertainty was reduced as much as possible by validation of the assumptions through industry experts.

The uncertainty of activity data forecasts can be evaluated by comparing the forecasts of the previous emission inventory (FOEN 2008) to the current figures for the year 2015. This corresponds to a forecast period of around 10 years as the previous inventory was based on data from 2000-2005. For 2015, the energy consumption of the current inventory was underestimated by 3% by the previous inventory (not counting electricity, as this was not part of the previous inventory). For some machine categories, the deviations are larger (i.e. the energy consumption of construction machinery was estimated 17% lower in the previous update), but they are partially compensated by deviations in other machine categories.

The *emission technologies used* can be mostly derived from the age distributions and the resulting emission standard that machines implement. There are two additional factors to be considered, however: On one hand, regarding PM, the degree of retrofitting diesel particle filters and the fact that different manufacturers follow different after-treatment strategies (discussed above) leads to uncertainty. Not all manufacturers selling equipment in Switzerland are covered in the Integer (2013) report on emission control technologies for stages EU-IIIB and –IV. Especially for agriculture, the manufacturers covered in the report only account for about half of the market share in Switzerland. Furhtermore, the market shares per manufacturer are only known for the historical periods (up to 2012) and they fluctuate over time. Therefore, the percentage of machinery equipped with DPF, especially in agriculture (Figure 3), is uncertain.

On the other hand, the implementation of new Euro emission stages is delayed due to two mechanisms in the EU Directives on non-road emissions that allow placing machinery on the market that conforms to the previous emission stage, i.e. the sell-off period and the flexibility scheme (EC 1997, EC 2014). The extent to which these two mechanisms are used is not known; therefore a sensitivity analysis was carried out. The difference in NO_x emissions between the "best-case" scenario (assuming immediate implementation of emission stages) and the "worst-case" scenario (assuming full exploitation of the two mechanisms) amounts to 14% of total emissions in the period 2015 to 2020. The emissions in the "most likely" scenario, to which the figures presented in this paper correspond (assuming a share 25% of conforming machines in the first year of a new emission stage, 50% in the second year and 100% from the third year, with a somewhat longer delay for stage IIIB), amount to almost exactly the average of the two extreme scenarios.

The *load factors* are generally one of the greatest sources of uncertainty in non-road emission calculations. For many machine categories, the only sources are estimates from industry experts. The changes in emissions due to adapting the load factors of construction machines based on the findings of Fridell et al. (2014; see also Chapter 0) give an impression of the magnitude of uncertainty: For the construction machines alone, energy consumption decreased by about 16% (depending on the reference year) due to the adaptation of the load factors. For the entire non-road inventory, this amounts to a decrease of about 6%.

Emission and energy consumption factors are obviously uncertain as well. This is due to the scarcity of measurements in general, and in particular due to the fact that the existing measurements were mostly carried out using the test cycles NRSC (Non-Road Steady Cycle) and NRTC (Non-Road Transient Cycle). Furthermore, for the emissions inventory presented here, there were virtually no measurements for newer machines (from stage EU-IIIB onwards) available at the time when modelling was carried out. Recent work by the Graz Technical University (Blassnegger 2014) using PEMS (Portable Emission Measurement Systems) measurements and the PHEM model shows that especially for NOx and newer construction machinery, emission limits are exceeded in real-world applications.

Finally, the *transition towards electric motors* is a large source of uncertainty in the future projections. So far, improvements in battery technology have caused a rise in popularity of electric equipment in areas of application where electric motors have been in use before, albeit less widespread, i.e. for industrial and hand-held devices. In the present Swiss non-road emissions inventory, the future projections for electric motors are limited to these areas of application. This results in a future stagnation of the electric share of non-road energy use, little above the current value of 5%, since the energy consumption of hand-held devices is low and the relative importance of industrial appliances is decreasing. However, very recent developments indicate that electric motors could become widespread in construction equipment (e.g. Bauwirtschaft Online 2014, Suncar-HK 2016), which could drastically change the outlook on NRMM emissions.

5 Conclusions

The new Swiss non-road emissions inventory delivers up-to-date figures on activity, energy consumption and emissions of NRMM in Switzerland. It documents the increasing activity of NRMM in the past decades and its importance among mobile emission sources. The simultaneous decrease in emissions demonstrates the effectiveness of legislation on emissions – primarily the EU directives on NRMM emissions, but also the Swiss national legislation on particle filter use on construction sites.

However, the modelled sharp decline of air pollutant emissions in the coming years is largely based on limit values and assumptions on the specific values of newer machines. Moreover, load factors remain a large source of uncertainty. The decline in emissions therefore must be verified with more measured data.

In order to do so effectively, increased international exchange of approaches, methods and data, as well as the coordination of measurement programs, are crucial. Currently, an initiative is planned by INFRAS and FOEN to enhance collaboration between non-road emissions experts in Europe.

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