THINKING
FOR
TOMORROW

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NRMM as a PM source in Switzerland: Results from the Swiss non-road inventory

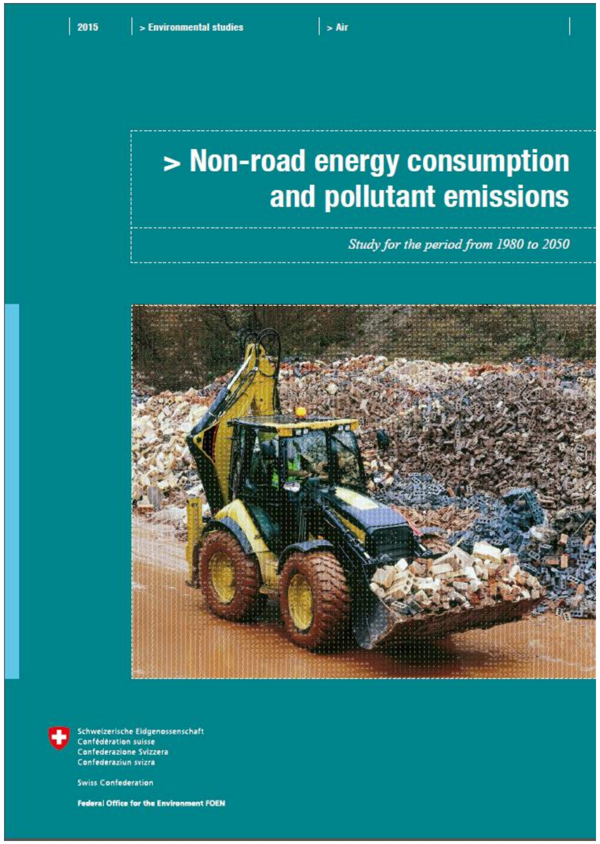
20th ETH Conference on Combustion Generated Nanoparticles, Zurich, June 13-16, 2016

Introduction: The Swiss non-road emissions inventory

- **Construction machinery:** e.g. excavators, load and dump trucks, rollers, generators, …
- **Industrial machinery:** e.g. forklifts, snow groomers, public works machinery, generators in commerce, airport airside vehicles/machinery
- **Agricultural and silvicultural machinery:** tractors, transporters, chainsaws etc.
- **Garden-care/hobby appliances:** chainsaws, lawn-mowers, blowers, …
- **Ships and boats:** motor boats, passenger ships, barges, …
- **Rail:** diesel locomotives
- **Military:** tanks, construction machinery, …

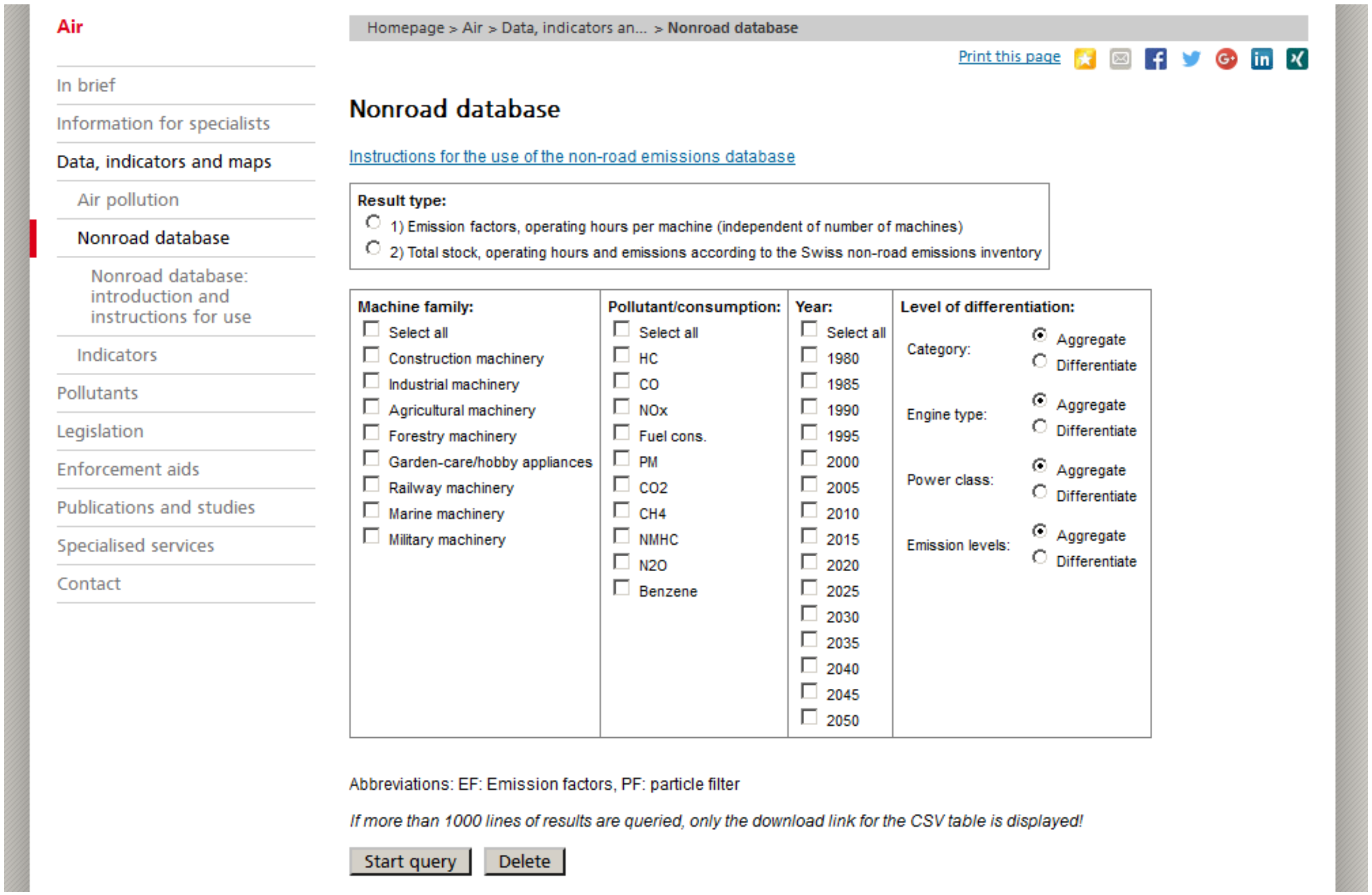
Publications

- First Swiss NRMM emissions inventory in 1996
- Updates:
  - 2008
  - 2015 (http://www.bafu.admin.ch/publikationen/publikation/01828/index.html?lang=en)
    → Time-series 1980-2050
    → Evaluation of impact of Swiss legislation, and aftertreatment strategies of manufacturers, on PM emissions



Online database

- http://www.bafu.admin.ch/luft/00596/06906/offroad-daten/index.html?lang=en



Limitations of the inventory regarding particulate emissions

- Only combustion as a PM source is considered; Non-exhaust sources are not (yet) included
- No differentiation of PM size classes or material – only total PM10, which is considered equal to PM2.5 (for exhaust PM)
- PM emissions are only modelled for diesel combustion.
  PM from petrol engines is not included (there are no legal PM limit values for non-road petrol engines)
- PN is also modelled, but results are not published due to low reliability (low availability of measurements for all EU stages)

Methods: NRMM emissions calculation formula

Energy requirement kWh

Correction factors

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

Emission/energy consumption factor

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)

→ Calculation by «subsegment», i.e. machine type, technology/aftertreatment, size class, emission standard

Methods: Base emission factor data sources

Engine power class	Pre-EU A	Pre-EU B	EU I	EU II	EU IIIA	EU IIIB	EU IV	EU V
Particulate matter (PM)								
<18 kW	1.51	1.18	1.00	0.80	0.70	0.60	0.60	*0.40*
18–37 kW	1.20	0.94	0.74[22]	0.60	0.54	→ 0.54	→ 0.54	*0.01*
37–56 kW	1.09	0.85	0.47	0.32	→ 0.32	0.03	0.03	*0.01*
56–75 kW	1.09	0.85	0.47	0.32	→ 0.32	0.03	0.03	*0.01*
75–130 kW	0.61	0.47	0.35	0.24	→ 0.24	0.03	0.03	*0.01*
130–560 kW	0.61	0.47	0.22	0.16	→ 0.16	0.03	0.03	*0.01*
>560 kW	0.61	0.47	0.22	0.16	→ 0.16	→ 0.16	→ 0.16	*0.05*

Sources of emission and consumption factors:
EPA data,
EPA data with reduction rate equivalent to that for black exhaust measurement data,
Homologation level plus manufacturing tolerance,
Average of homologation and limit value,
Division of limit value for total of HC + NOx, less 10 %,
Maximum level less 30 %,
Maximum level less 10 %,
Emission limit value
Assumption or adoption of figure from another emission stage (arrow).

- Pre-Euro: US EPA data with reduction rates based on EMPA/Agroscope/IVECO PM measurements
- EU-I, -II, -IIIA: Type approval values plus (or minus) tolerance, or average of TA and limit
- EU-IIIB – EU-IV: Limit values
- EU-V: Limit values, type approval values of existing machinery with DPF for 18-560 kW

Methods: Correction factors for DPF use

Uncorrected and corrected EF, construction machinery

Base EF
(=EF assuming minimal EU compliance)

SizeClass	PreEUA	PreEUB	EU1	EU2	EU3A	EU3B	EU4	EU5
<18 kW	1.505	1.175	1.000	0.800	0.700	0.600	0.600	0.400
18–37 kW	1.200	0.941	0.738	0.596	0.540	0.540	0.540	0.400
37–56 kW	1.090	0.849	0.475	0.318	0.318	0.025	0.025	0.015
56–75 kW	1.090	0.849	0.475	0.318	0.318	0.025	0.025	0.015
75–130 kW	0.606	0.473	0.355	0.238	0.238	0.025	0.025	0.015
130–300 kW	0.606	0.473	0.224	0.165	0.165	0.025	0.025	0.015
300–560 kW	0.606	0.473	0.224	0.165	0.165	0.025	0.025	0.015
>560 kW	0.606	0.473	0.224	0.165	0.165	0.165	0.165	0.045

DPF correction factors

SizeClass	PreEUA	PreEUB	EU1	EU2	EU3A	EU3B	EU4	EU5
<18 kW	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.150
18–37 kW	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.135
37–56 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
56–75 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
75–130 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
130–300 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
300–560 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
>560 kW	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.366

Resulting EF
(with DPF)

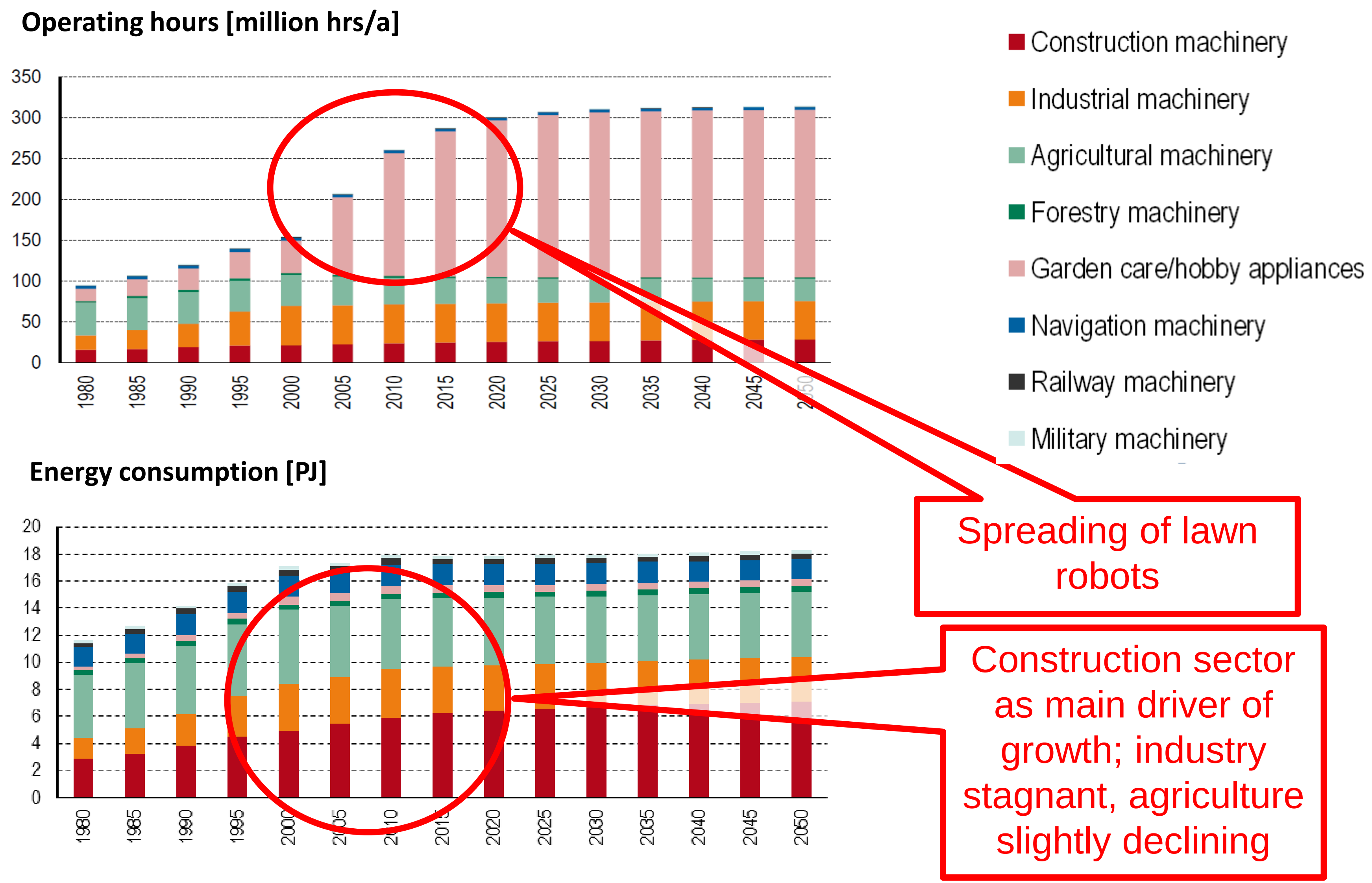
SizeClass	PreEUA	PreEUB	EU1	EU2	EU3A	EU3B	EU4	EU5
<18 kW	0.151	0.118	0.100	0.080	0.070	0.060	0.060	0.060
18–37 kW	0.120	0.094	0.074	0.060	0.054	0.054	0.054	0.054
37–56 kW	0.109	0.085	0.047	0.032	0.032	0.015	0.015	0.015
56–75 kW	0.109	0.085	0.047	0.032	0.032	0.015	0.015	0.015
75–130 kW	0.061	0.047	0.035	0.024	0.024	0.015	0.015	0.015
130–300 kW	0.061	0.047	0.022	0.016	0.016	0.015	0.015	0.015
300–560 kW	0.061	0.047	0.022	0.016	0.016	0.015	0.015	0.015
>560 kW	0.061	0.047	0.022	0.016	0.016	0.016	0.016	0.016

Methods: Diesel particle filter (DPF) use

- Machinery > 18 kW on construction sites: DPF requirement by law (Swiss ordinance on Air Pollution Control OAPC)
- Other machinery:
  - Aftertreatment strategy for EU-IIIb, EU-IV by manufacturer based on Integer (2013)
  - Market shares by manufacturer based in Off-Highway Research (2008, 2012)

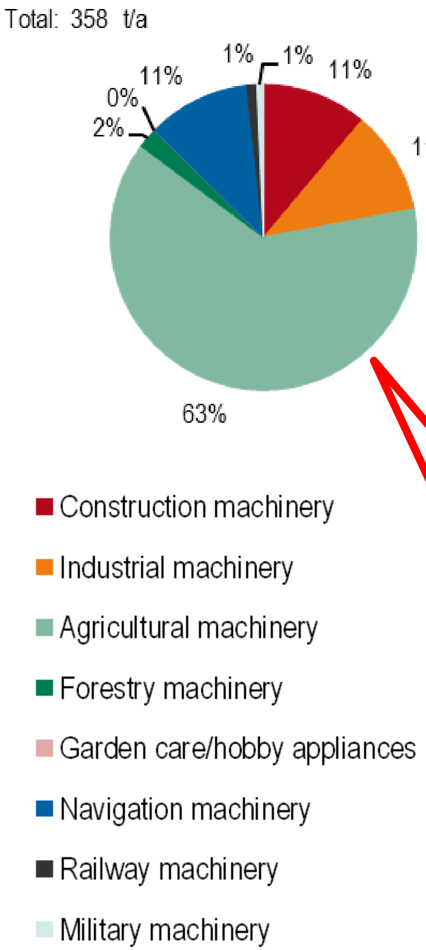
Manufacturer	Stage EU-IIIB / US Tier 4 Interim	Stage EU-IV / US Tier 4 Final
AGCO	No	No
Caterpillar	Partially	Yes
CNH	No	No
Cummins	Partially	Partially
Deutz	Partially	Yes
IHI	No	No
Isuzu	Partially	No
John Deere	Partially	Yes
Komatsu	Partially	Partially
Kubota	Partially	Yes
Liebherr	Partially	No
Takeuchi	No	No

Results: Development of NRMM activity



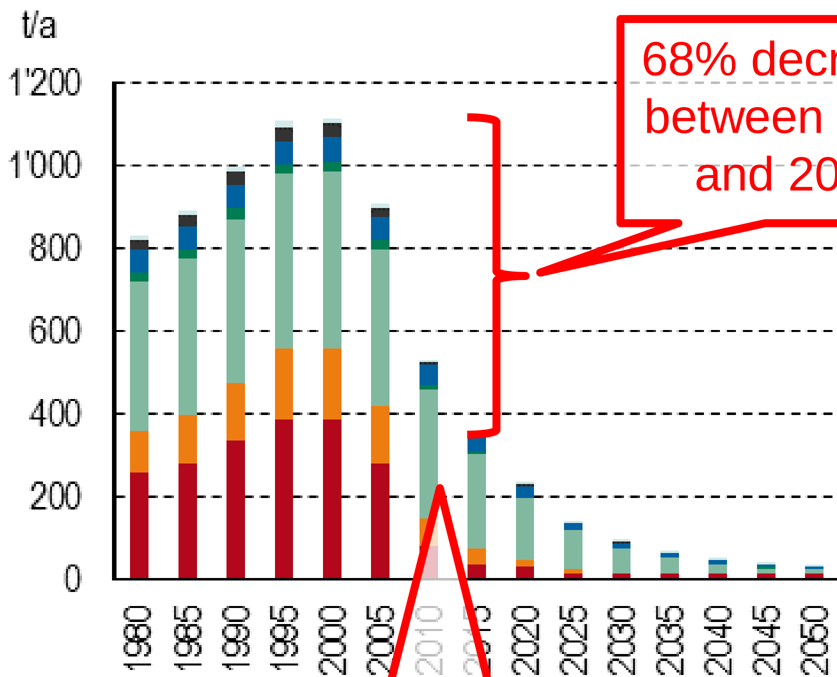
Results: PM10 emissions

a) Shares in 2015



Agriculture (63%) by far the largest emitter, followed by construction, industry and ships

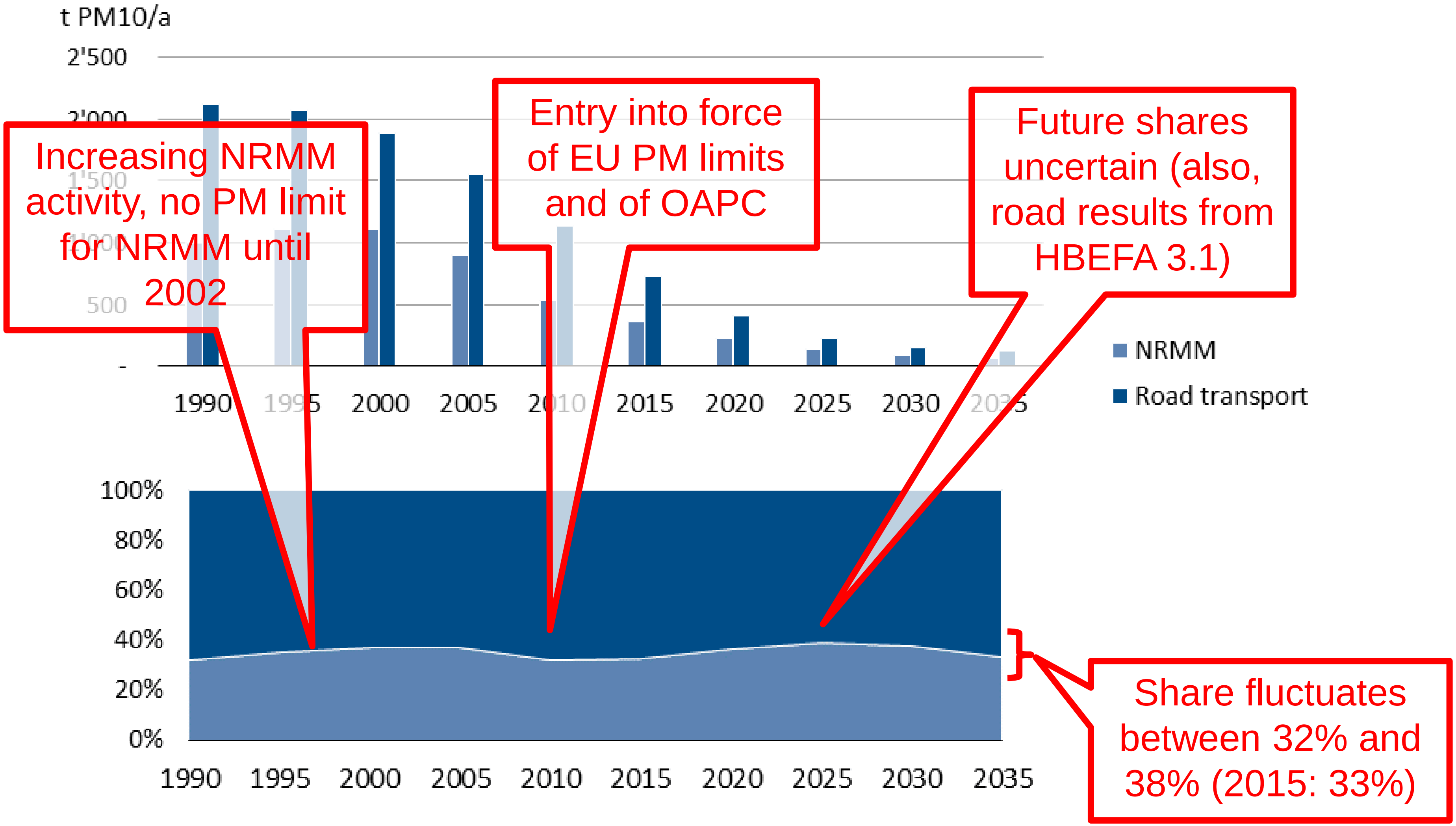
b) Time series 1980-2050



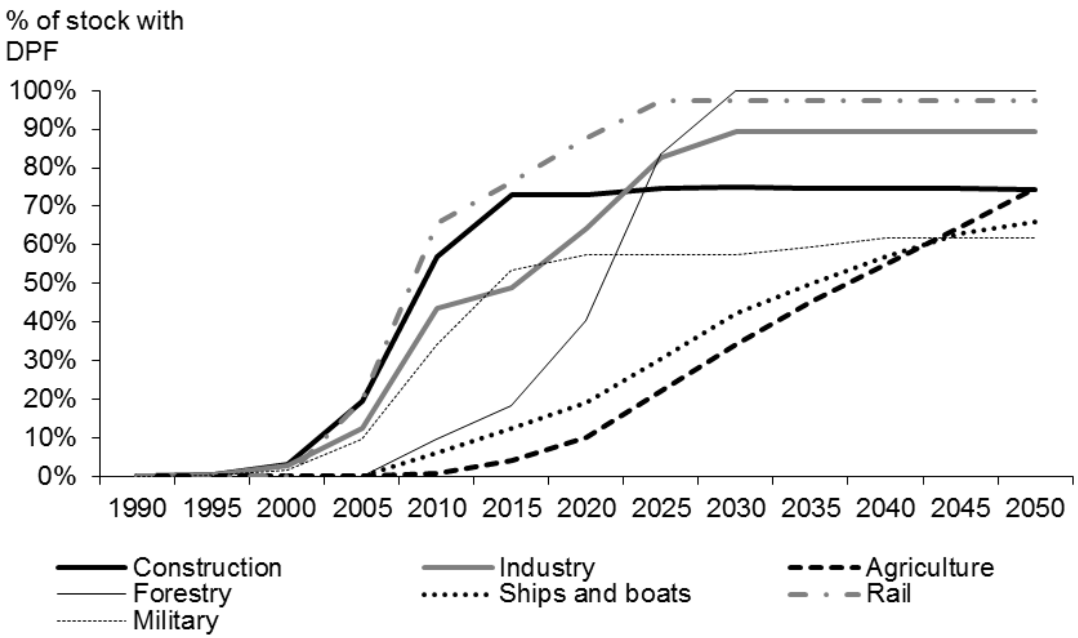
68% decrease between 2000 and 2015

Construction used to emit almost as much PM as agriculture, but emissions have sharply declined

Results: Road vs. non-road, development

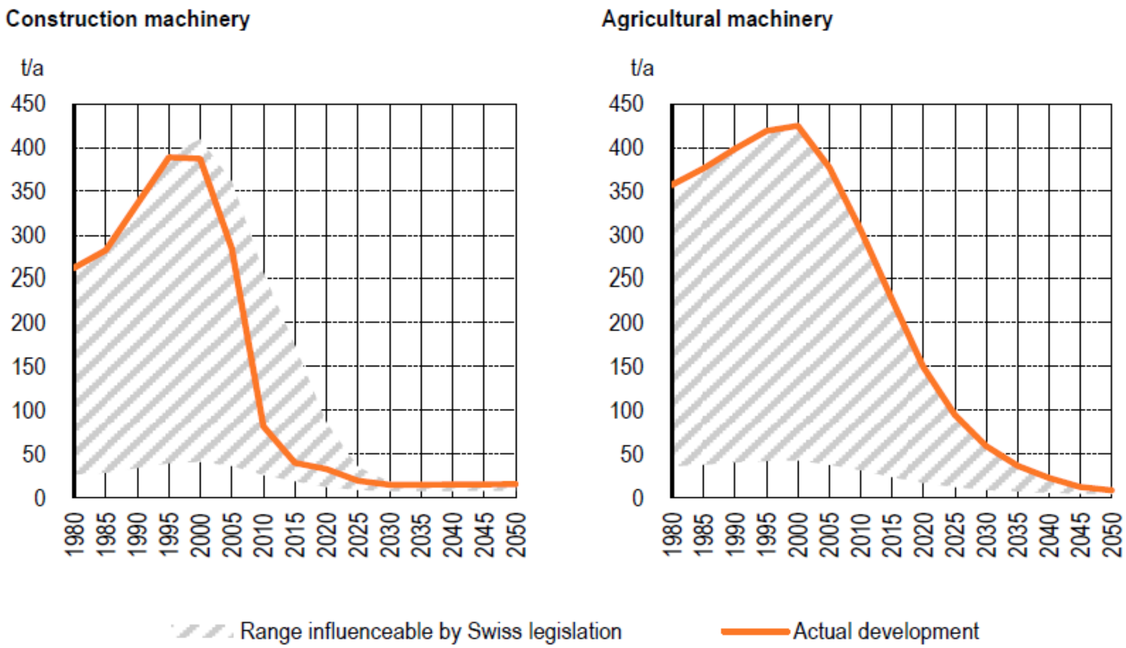


Results: Impact of legislation on DPF use



- Construction machinery: Rapid increase up to >70% in 2000-2010 due to OAPC; stagnation afterwards as no DPF requirement for machines <18 kW
- Agricultural machinery: slow increase due to absence of regulations beyond EU limits and long life cycles

Results: Impact of legislation on PM emissions



- In 2015, PM emissions from construction machinery are 77% below the level with minimal DPF use based on EU legislation
- PM emissions from agricultural machinery are only 1% below the level with minimal DPF use
- In total, NRMM emissions are 34% below minimal DPF level (also due to voluntary measures e.g. from rail operators)

Conclusions

- PM10 (exhaust) emissions from NRMM are rapidly decreasing
- This is mainly a result of
  - EU legislation (NRMM directive 97/68/EC and related directives) → general decrease
  - Swiss legislation (OAPC, BauRLL) → rapid decrease in construction machinery
- However, large uncertainty to which extent modelled decline of emissions is real
  → more measurements are necessary, especially of newer machines
  → real-world machine loads need to be assessed
  → More international cooperation between emission modellers is needed!
  → Switzerland: DPF use, especially in agriculture, needs to be monitored

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Thank you for your attention!

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Objectives of the 2015 update

- Modelling period 1980 – 2050 (previously up to 2020) → include Euro-V
- Include electric devices that replace NRMM with combustion engines
- Include non-regulated pollutants CH_4, NMHC, benzene, N_2O
- Include some machine types that were previously neglected (generators in industry, commerce and public administration, barges on Rhine river, vehicles and machinery of airside sector of airports)
- **Assess diesel particle filter (DPF) use and impacts of Swiss legislation**
- Assess impact of delayed implementation of emission standards

Methods: Activity data sources (general)

- Official statistics (e.g. vehicle registration database, agricultural census, import/export statistics, fuel tax refunds)
- Market studies (e.g. Off-Highway Research, Integer Research)
- Questionnaires sent to operators
- Expert workshops
- Previous inventory versions
- Trend scenario up to 2050: sectoral economic forecasts, population forecasts, long-term planning of railway operators and military, forward projection of trends with gradual level-off

Methods: Model adaptions for DPF use

Model published in FOEN (2008):

- DPF correction only for retrofitted machinery.
- Assumption that from EU-IIIB compliance could only be reached with DPF and thus all machinery would be fitted with DPF ex-works.
- Constant correction factor values (PM: EF – 90%, FC: CF + 3%)

Adapted model (FOEN 2015):

- Compliance with limit values of EU-IIIB and –IV is also possible without DPF → only partial fitting of DPF by manufacturers
- Therefore, correction factor is applied for all machinery fitted with DPF, but differentiated by machine category, size class and emission standard, so that from EU-IIIB target EF of 0.015 g/kWh results

Methods: Correction factors for DPF use

Uncorrected and corrected EF, construction machinery

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300–560 kW	0.100	0.100	0.100	0.100	0.100	0.600	0.600	1.000
>560 kW	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.366

Resulting EF
(with DPF)

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EU-IIIA to –IV: Where limit value <0.03, DPF can reduce EF by additional 40% only

EU-V: Where limit value for PN, DPF is necessary, therefore no correction required

Up to EU-IIIA: 90% reduction with DPF (as in old model)

EU-V: For size classes without limit value for PN, correction factor must result in equal final EF as under previous emission standards

Methods: Sources of historical DPF use

- Previous NRMM inventory (FOEN 2008):
  - Survey of manufacturers and retrofitters of DPF
  - Study by TTM (2004) on the implementation of the «Baurichtlinie Luft» (Directive on clean air on construction sites)
  - Consultation on the revision of the SAV (ordinance on ship emissions)
  - Information by SBB (Swiss Federal Railways)
- Swiss vehicle registration database (MOFIS)

Methods: DPF use, EU-IIIB + EU-IV

- Machinery > 18 kW on construction sites: DPF requirement by law (Swiss ordinance on Air Pollution Control OAPC)
- Other machinery:
  - Aftertreatment strategy for EU-IIIb, EU-IV by manufacturer based on Integer (2013)
  - Market shares by manufacturer based in Off-Highway Research (2008, 2012)

integer **Caterpillar**

Background

- Caterpillar was originally active in both the on-highway and off-highway sectors – it stopped most of its on-highway business in 2010. It is an important supplier in other diesel engine markets: defence, locomotive, marine and mining. Caterpillar operates as an OEM and a tier supplier; manufacturing its own range of off-highway agricultural and construction machinery, as well as supplying Cat- or Perkins- branded engines to its competitors.
- Caterpillar has transferred its experience of emissions reduction in the on-highway sector to its engine design for the off-highway sector, and in doing so has leveraged its ACERT-branded technology.

Emissions control strategy

- Caterpillar's announced Tier 4 (interim and full) strategy is an extension of its 2007 and aborted 2010 on-highway Advanced Combustion Emission Reduction Technology (ACERT) system. This is essentially a package of air-management and in-cylinder improvements supporting an EGR system, although the company has sought to avoid using the term EGR in any of its brochures and publicity materials.
- Instead, the system is referred to as the Cat NOx Reduction System in order to avoid the negative connotations implied by the term EGR. The system also includes a number of after-treatment components like a diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF), together with SCR for Tier 4 Final.
- The company used ACERT in off-highway applications for Tier 3, though the technology package was much simpler. For Tier 4 interim Cat is using a low pressure EGR loop in tandem with common rail high pressure fuel injection, series turbochargers, multi-shot injection and an improved engine control unit.
- In March 2011 the company officially announced that it shall be using SCR in tandem with its existing ACERT technology in order to meet Tier 4 Final standards for off-highway engines.
- Intermat 2012 (April) saw the Tier 4 Final, C13 ACERT and C7.1 ACERT engines unveiled, featuring SCR technology - followed by the C9.3 ACERT Tier 4 Final in October 2012. By Bauma 2013 the entire engine range had been updated at both Caterpillar and Perkins. SCR will also be used across its entire range of off-highway engines above 56kW for Tier 4 Final with DPF optional on all engines.

Table 21. Switzerland: Suppliers of Crawler Excavators and Their Market Shares, 2007-2011

(Units)

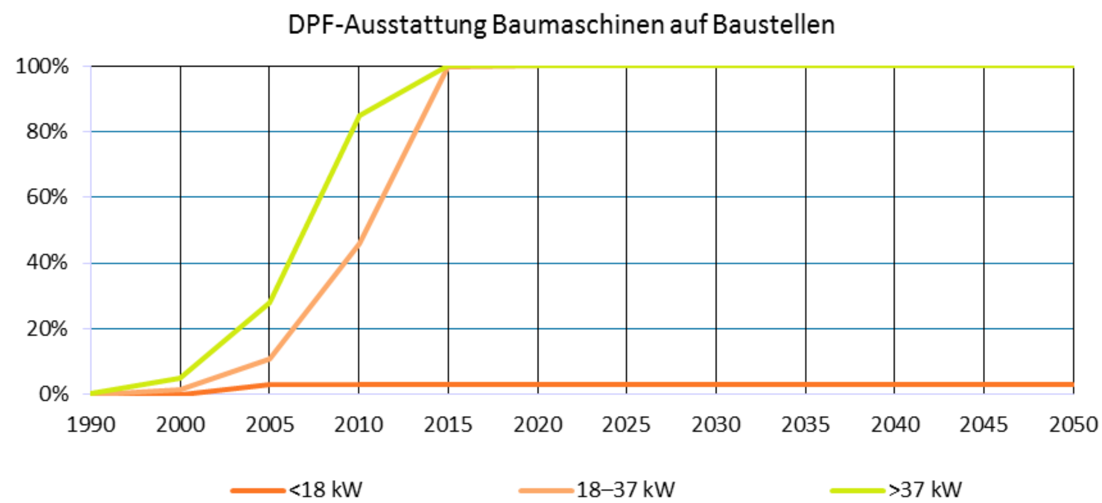
	2007		2008		2009		2010		2011	
	Units	%	Units	%	Units	%	Units	%	Units	%
Caterpillar	194	24	128	17	135	22	142	20	141	20
Komatsu	94	12	97	13	75	12	99	14	89	13
Takeuchi	75	9	86	11	73	12	70	10	67	10
Volvo	60	7	69	9	62	10	66	9	66	9
Hitachi	71	9	54	7	53	9	74	10	54	8
Liebherr	37	5	48	6	27	4	41	6	43	6
New Holland	50	6	47	6	25	4	25	4	41	6
Wacker Neuson	32	4	22	3	18	3	24	4	39	6
Kobelco	63	8	71	9	49	8	45	6	25	4
Kubota	11	1	37	5	16	3	44	6	25	4
Case	6	1	-	-	-	-	-	-	22	3
JCB	-	-	14	2	5	1	9	1	17	2
Hyundai	30	4	17	2	15	2	20	3	16	2
IHI	-	-	14	2	18	3	18	3	14	2
Yanmar	11	1	25	3	17	3	12	2	13	2
Terex	3	-	5	1	2	-	7	1	8	1
Mecalac	-	-	-	-	-	-	-	-	8	1
Doosan	16	2	15	2	9	1	8	1	8	1
Nagano	2	-	1	-	-	-	-	-	-	-
Kato	48	6	-	-	18	3	-	-	-	-
Bobcat	5	1	-	-	-	-	-	-	-	-
Total	808	100	750	100	617	100	704	100	696	100

Source: Off-Highway Research

Methods: DPF use on contruction sites (OAPC)

In-Kraft-Treten und Übergangsfristen der LRV-Bestimmungen

Leistung der Maschine	Baujahr	LRV-Konformität notwendig ab
ab 37kW	ab 2009	1. Januar 2009
	2000–2008	1. Mai 2010 auf B-Baustellen: 1. Januar 2009
	vor 2000	1. Mai 2015
18kW–37kW	ab 2010	1. Januar 2010

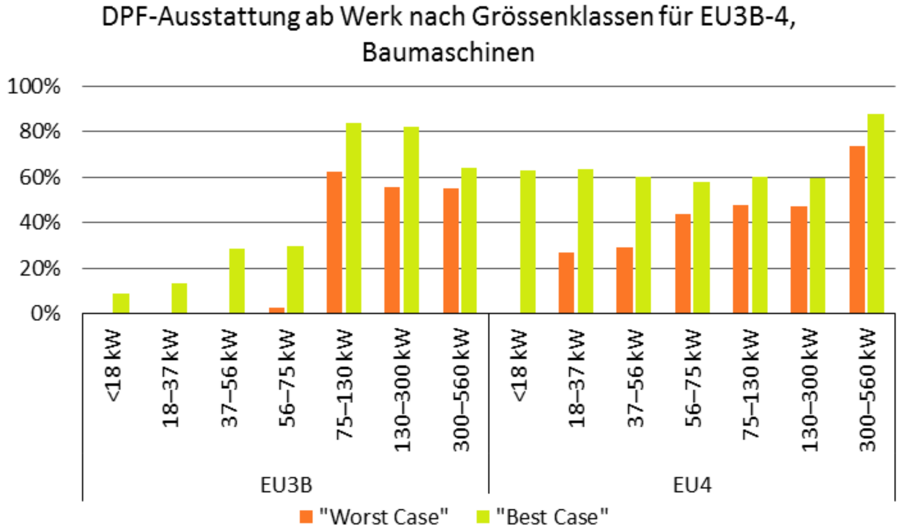


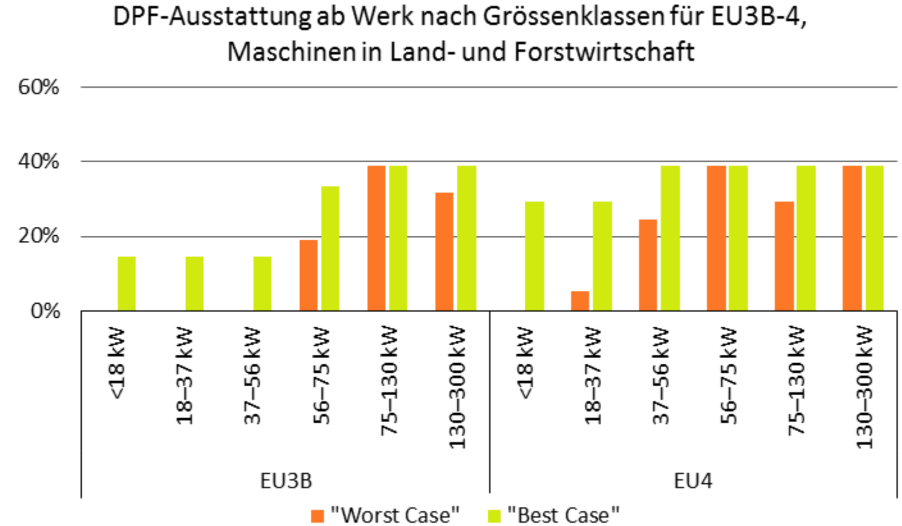
SizeCLass	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
<18 kW	3%	3%	3%	3%	3%	3%	3%	6%	9%	15%	3%	3%	3%	3%	3%	3%
18–37 kW	11%	17%	23%	28%	34%	46%	57%	69%	80%	90%	100%	100%	100%	100%	100%	100%
>37 kW	28%	35%	42%	49%	58%	85%	89%	92%	95%	97%	100%	100%	100%	100%	100%	100%
56–75 kW	28%	35%	42%	49%	58%	85%	89%	92%	95%	97%	100%	100%	100%	100%	100%	100%
75–130 kW	28%	35%	42%	49%	58%	85%	89%	92%	95%	97%	100%	100%	100%	100%	100%	100%
130–300 kW	28%	35%	42%	49%	58%	85%	89%	92%	95%	97%	100%	100%	100%	100%	100%	100%
300–560 kW	28%	35%	42%	49%	60%	85%	89%	92%	95%	97%	100%	100%	100%	100%	100%	100%

= LRV 18-37 kW
= LRV >37 W, Baujahr ab 2009
= LRV >37 kW, inkl. Baujahre vor 2000
= LRV > 37, Baujahr ab 2000

Methods: DPF ex-works, EU-IIIB/IV

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



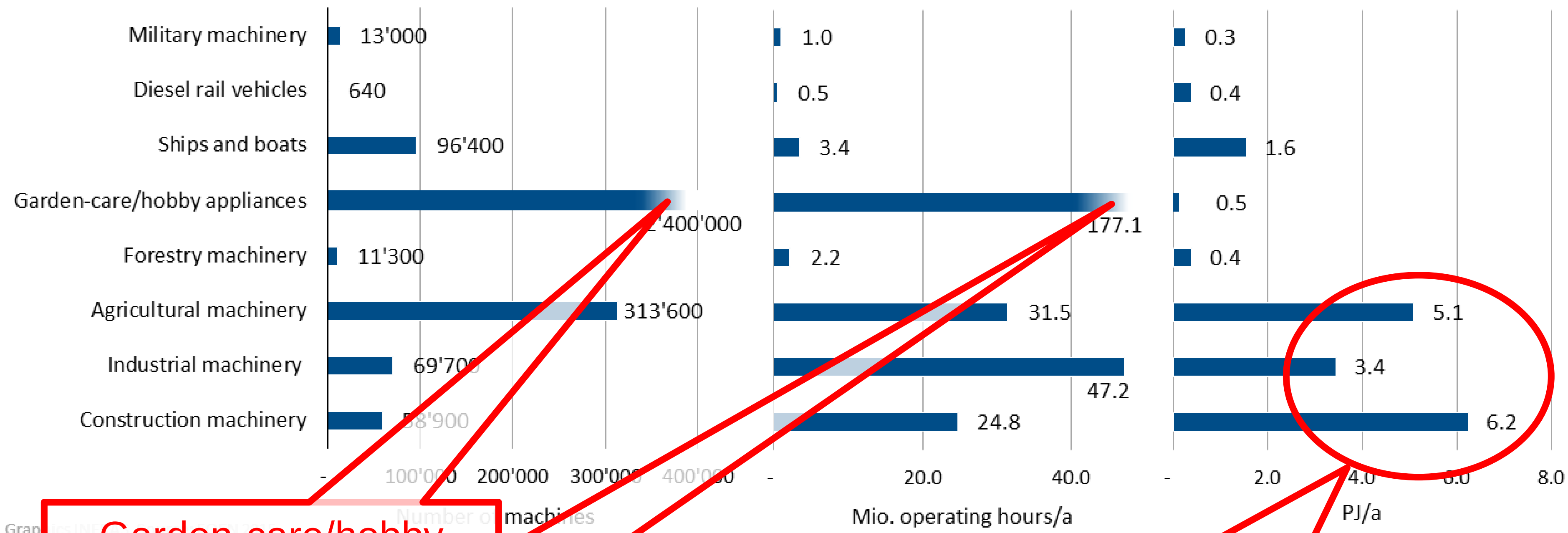


Methods: Shares of activity on construction sites

Maschinenkategorie	Anteil auf Baustellen
Strassenfertiger	100%
Rammbären aller Art mit Hydraulik-Aggregaten	95%
Walzenzüge aller Art	100%
Vibratoren maschinell	100%
Stampfer, Vibratoren handgeführt	100%
Hydraulik-Bagger	93%
Minibagger	67%
Raupenbagger	85%
Radbagger	85%
Seilbagger	100%
Pneu-/Mobilkräne	100%
Grader	95%
LKW ohne Strassen-Zulassung	100%
Planierraupen	75%
Lader (Pneu & Raupen) aller Art	60%
Dumper/Kipper	96%
Notstromaggregate/Generatoren	100%
Pumpen aller Art	95%
Kompressoren aller Art	100%
Hubarbeitsbühnen	100%
Tunnel-Lokomotiven	100%
Beton-/Belagfräsen	100%
Grabenfräse	95%
Bohrgeräte aller Art (spez. Tiefbau)	95%

Results: Activity and energy consumption, 2015

TOTAL: 3 million machines 290 million hrs/a 17.9 PJ/a



Garden-care/hobby appliances: Largest stock and longest operating hours (lawn robots) – but no PM emissions modelled

Largest energy consumers (powerful diesel engines) – and PM emitters

Results: Comparison road vs. non-road, 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%

Sources of uncertainty

- **Stock and operating hours:** Based on official data sources and market studies for larger machinery, large degree of estimation for smaller devices
- **Emission technologies used (especially DPF):** Mainly uncertain for agriculture (only half of market covered by studies consulted, unknown impact of cantonal measures/incentives for retrofitting)
- **Load factors:** One of the greatest sources of uncertainty. For construction machinery, energy consumption decreased by 16% after adapting load factors based on Fridell et al. (2014)
- **Emission factors:** Scarcity of emission measurements, therefore reliance on type approval data and estimates. Large sensitivity especially for later Euro stages (from IIIB) leads to uncertainty to which extent modelled emission reductions are achieved in reality
- **Transition towards electric motors:** Subject to speculation at the moment