

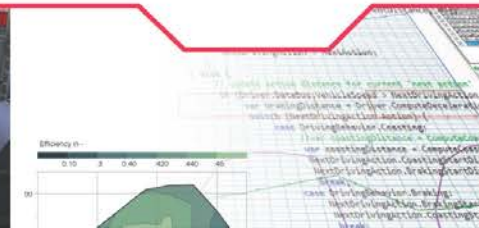
Non-Road Mobile Machinery

Electrification potentials and real-world emissions

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Background

- NRMM responsible for
 - 3.1 % of total CO₂-equivalent emissions in EU¹
 - 15 % of total NOx¹ and 39 % of total particle mass² emissions
- No CO₂ regulation in place for NRMM
 - Slow transition from fossil ICE to alternative off-road powertrains
- Research projects
 - Elaboration of electrification potentials of NRMM³
 - Update of emission factors for national emission inventories⁴

¹ T&E: Reducing emissions from non-road mobile machinery, briefing, december 2024

² Anderl, M., et al.: Austria's national inventory document 2025, Umweltbundesamt GmbH, Vienna, 2025

³ Funding agencies: Environmental Agency Germany and Federal Ministry for the Environment Germany

⁴ Funding agencies: Environmental Agencies of Austria and Switzerland and the European Commission for EMEP/EEA Guidebook

ICE: Internal Combustion Engine

NRMM: Non-Road Mobile Machinery

Electrification potentials – Goal and boundary conditions

- Goal of FVT / TU Graz work⁵
 - Elaborate electrification potential for NRMM
- Boundary conditions
 - Assessment of technical feasibility
 - TCO analysis on a few examples for checking economical feasibility
 - Sensitivity analysis for checking base data uncertainty
 - Focus on electrification first
 - Simplified analysis of feasibility of alternatives (hydrogen or other CO₂ neutral fuels)
 - Analysis for 2030 and 2050
 - Sectors covered: construction, agriculture and forestry machinery and inland waterway shipping

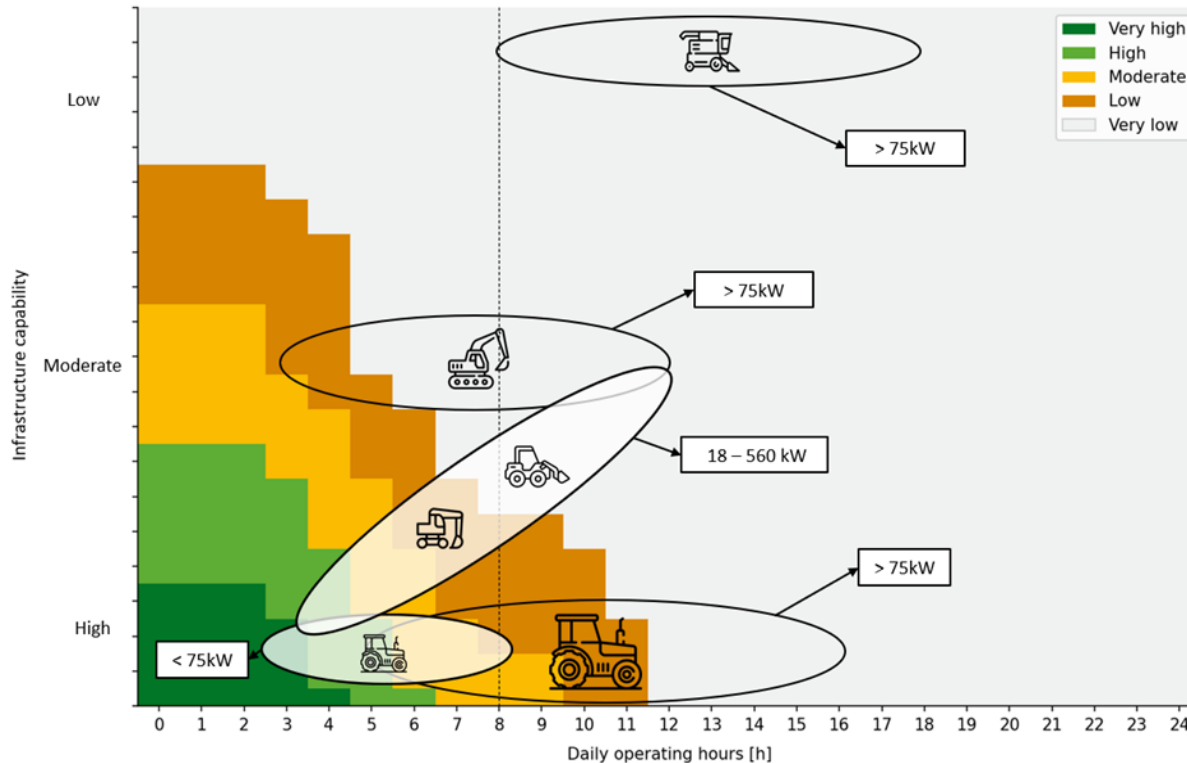
⁵ task of additional consortium members: ifeu – assessment of effect on overall emissions, ICCT – policy recommendations and regulatory options
TCO: Total Costs of Ownership

Methodology

$$\text{Electrification potential} = F_{\text{charging}} \times F_{\text{battery}} \times F_{\text{grid connection}} + F_{\text{special solution}}$$

- Each factor determined independently ranging from 0 to 1
 - multiplicative approach: if one factor is 0 → electrification potential is 0
- Calculation of energy demand per working day [kWh] based on working hours [h] and load factors [kW]
 - In total for 176 segments (covering machine and power categories)
 - Standard and high volume working day
 - Data input from: VDMA, OEMs, TU Graz, ifeu, ICCT, surveys of CH and LU, scientific studies⁶, NGOs, National and EU authorities
 - Expert discussions on the results

Electrification potential 2050 for agricultural, forestry and construction machinery

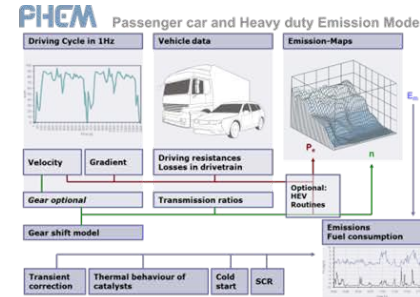


- Higher daily operating hours (often connected to high engine power) → lower EP
- Limited availability of infrastructure capability → low EP
- Machine segments with working hours less than half shift and specific well-known operation spots can be fully electrified
- Alternative solutions beside electrification demanded for CO₂ neutrality → hydrogen or other CO₂-neutral fuels

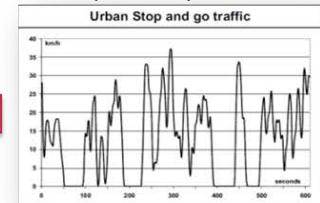
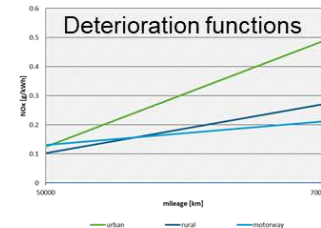
Update of emission factors for emission inventories

- Diesel driven machines will remain dominant in the upcoming years
- Demand for update of emission factors with focus on stage IV and V
 - Last update more than 10 years ago
 - No real-world data for stage V

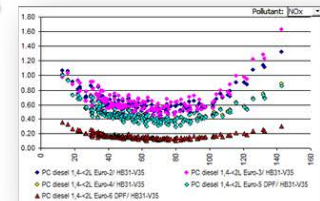
Real world test data



Operation profiles



Emission factors



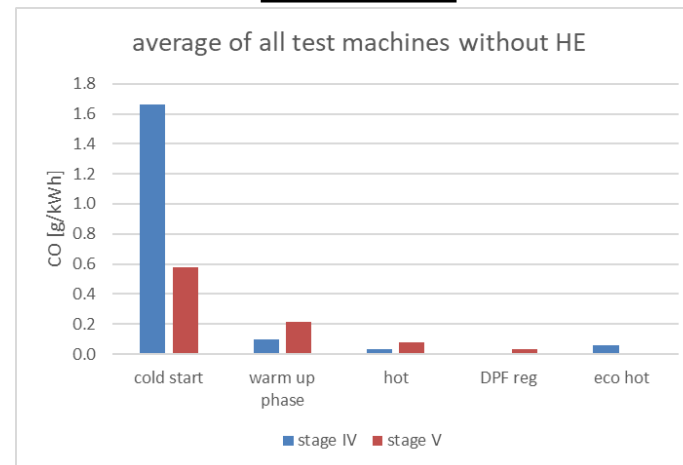
Real-world test data base

- Test of 11 stage IV and V machines at FVT/ TU Graz
 - real-world operation separated in operation phases
 - Test of new and “old” machines (between 320 and 6 600 operation hours)

- CO emissions
 - Cold start effect clearly visible
 - Emission level clearly below limits in all operating phases



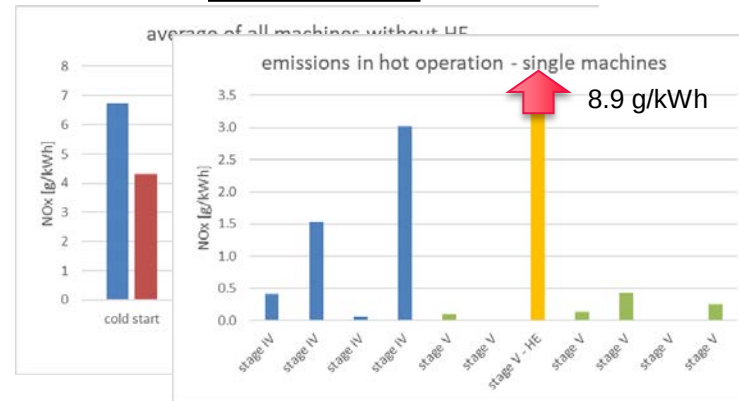
CO emissions



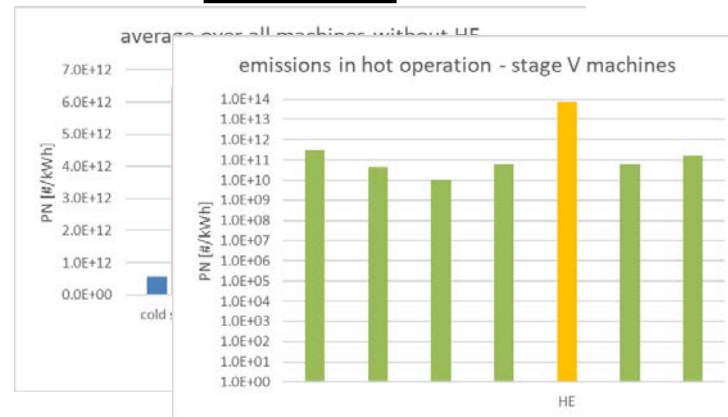
Real-world test data base

- NOx emissions
 - Emission increase during cold start and warm up phases
 - Stage V below limit in hot operation, stage IV on a higher level
 - Raising emissions during DPF-regeneration
 - High spread between single machines
- PN emissions
 - Stage V lower in hot operation, but higher emissions in cold start, warm up and DPF-regeneration phase
 - High emitter 670 times higher in hot operation than average stage V

NOx emissions



PN emissions

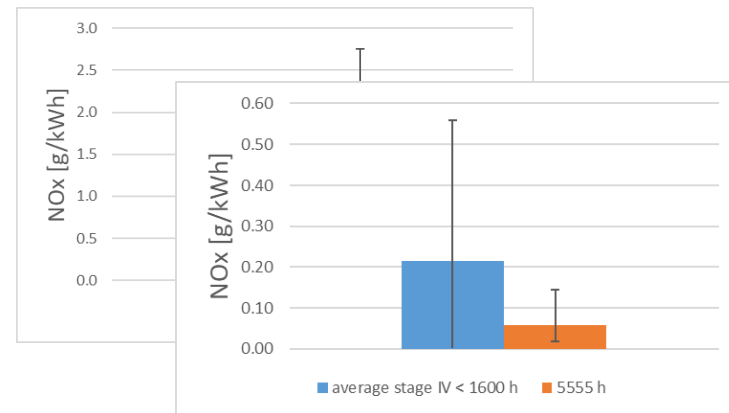


Analysis of ageing effects

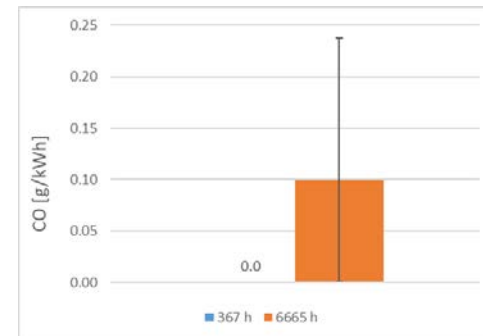
- NOx emissions
 - Ageing effects visible for most stage IV machines
 - No effects visible for stage V
 - So far only 2 test machines with high operating hours
 - Operating hours smaller than for stage IV

- CO emissions
 - No significant effect for stage IV visible
 - Emission increase for 1 of 2 stage V machine pairs

NOx emissions - stage IV machines

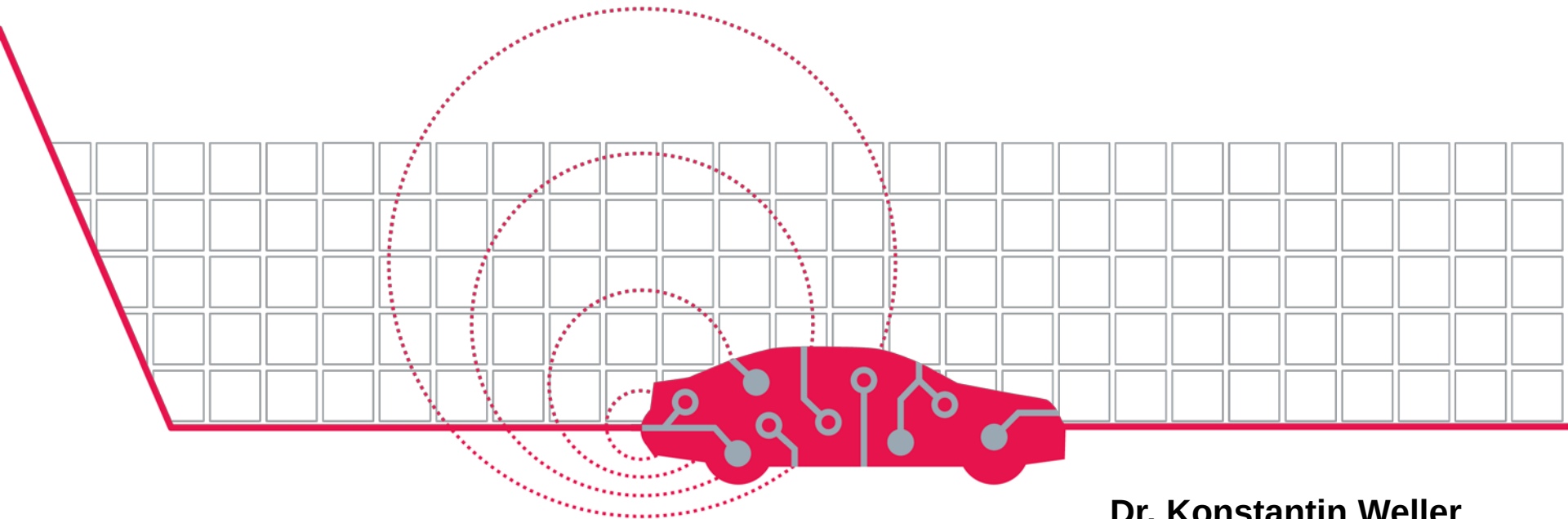


CO emissions - stage V machine



Conclusion

- Electrification potential
 - Decreasing electrification potential with increasing engine power
 - Demand for alternative solutions for CO₂-neutrality
 - Final report: <https://www.umweltbundesamt.de/publikationen/enrmm>
- Emission factors: demand for update
 - Real world test data
 - High spread between single machines, e.g. due to ageing effects
 - Significant emission increase due to manipulation/defects
 - Further test data very welcome!
 - Further tests planned at TUG/FVT + data from other labs available
 - ISM data base
 - Emission modelling ongoing work



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Methodology

$$\text{Electrification potential} = F_{\text{charging}} \times F_{\text{battery}} \times F_{\text{grid connection}} + F_{\text{special solution}}$$

- Factor charging: Can the battery be recharged? (overnight, opportunity, swapping)
- Factor battery: Can the battery be installed in the machine?
- Factor grid connection: Is there infrastructure available on site to setup charging infrastructure?
- Factor special solution: Optional, consideration of special solutions e.g. catenary operation etc.
- Each factor determined independently ranging from 0 to 1
 - multiplicative approach results in potential ranging from 0 to 1
 - if one factor is 0 → electrification potential is 0

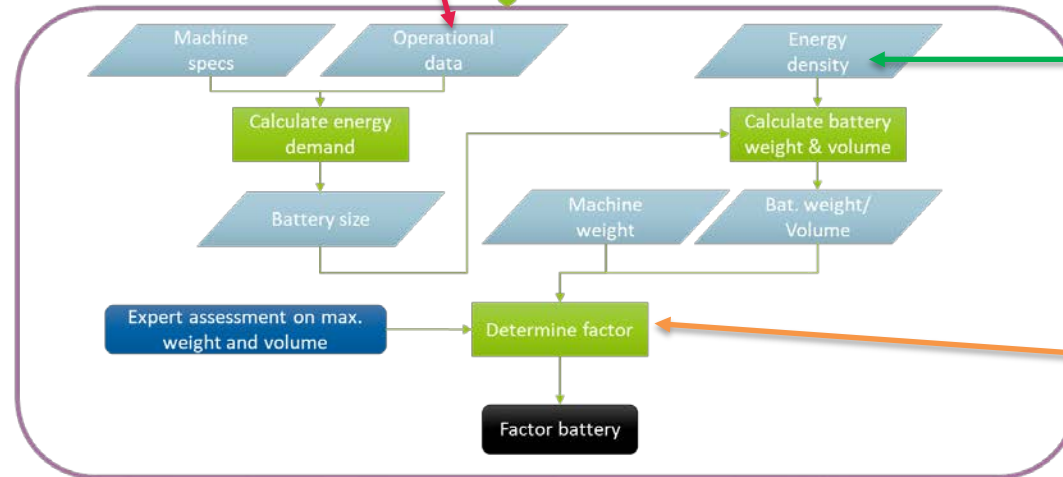
Methodology – factor battery as example

kWh = Work duration [h] x load factor [kW]

- Sec-by-sec data, values per work day or year
- VDMA, OEMs, TU Graz, ifeu, survey CH, survey LU

Consideration of standard and high-volume working days

Electrification potential = $F_{\text{charging}} \times F_{\text{battery}} \times F_{\text{grid connection}} + F_{\text{special solution}}$



Battery specifications

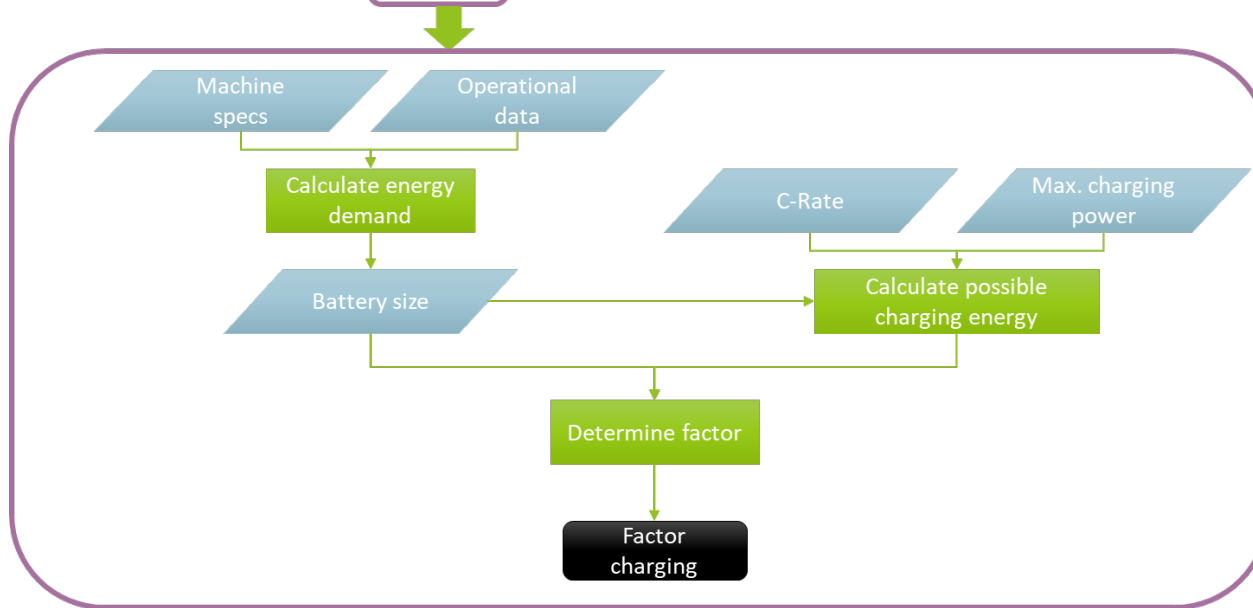
- Specific energy, energy density, C-rate
- Expert discussions, scientific studies (main documents from Fraunhofer²)

Result discussions with stakeholders

- Project partners, VDMA, OEMs, NGOs, National and EU authorities

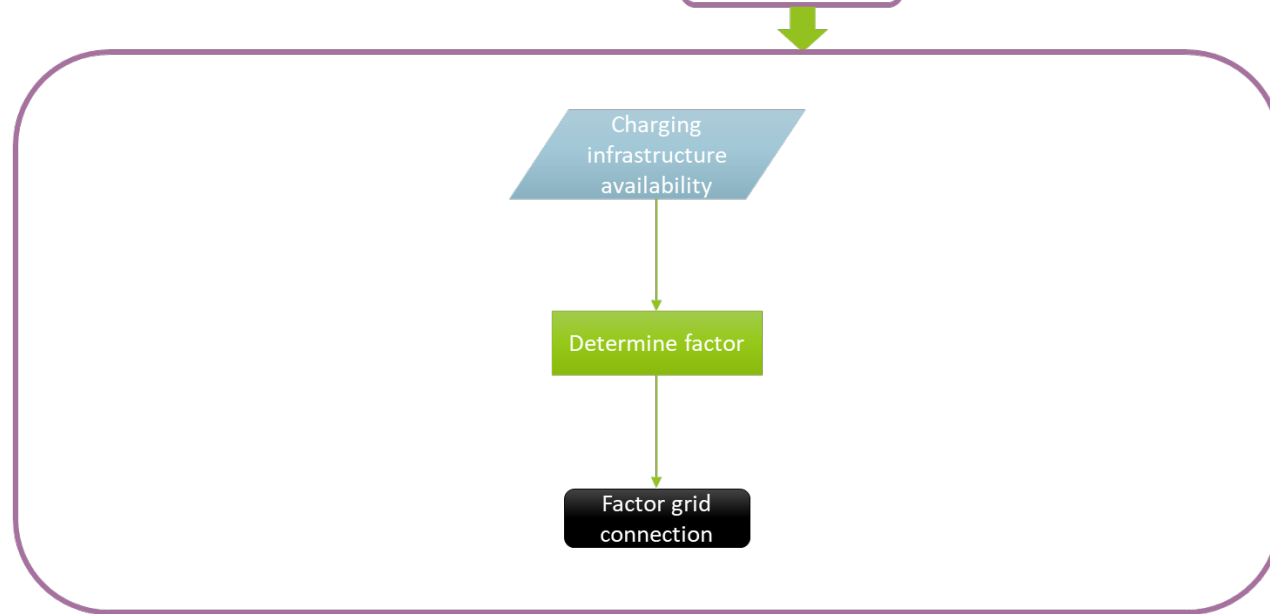
Methodology – factor charging

$$\text{Electrification potential} = F_{\text{charging}} \times F_{\text{battery}} \times F_{\text{grid connection}} (\times F_{\text{specific}}) + F_{\text{special solution}}$$



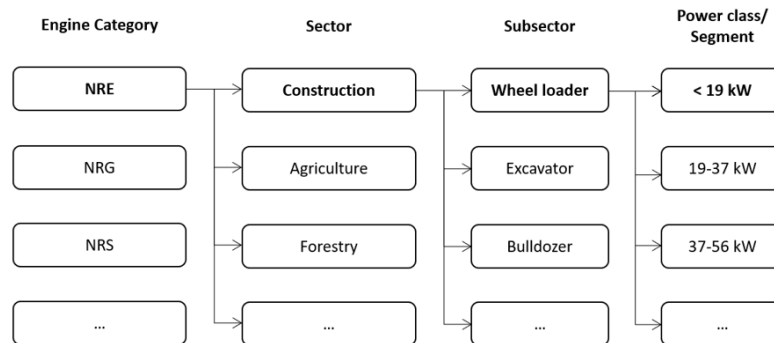
Methodology – factor infrastructure

$$\text{Electrification potential} = F_{\text{charging}} \times F_{\text{battery}} \times F_{\text{grid connection}} (\times F_{\text{specific}}) + F_{\text{special solution}}$$



Methodology – segmentation and result rating

- Machine segmentation:
176 segments in total



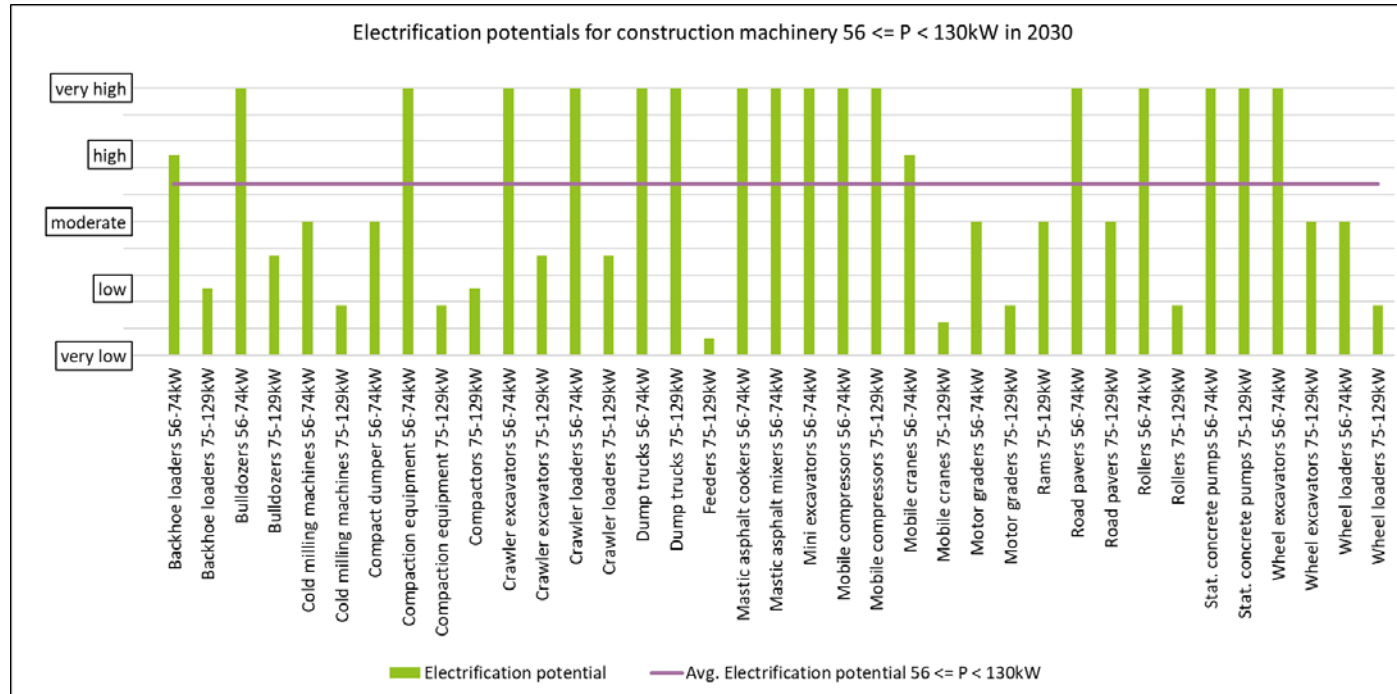
- Result rating:
Limited data availability
leads to a degree of
uncertainty

Classification	E-Potential from	to
Very high	80%	100%
High	60%	80%
Moderate	40%	60%
Low	20%	40%
Very low	0%	20%

NRE: Non-Road Engines
 NRG: Non-Road Generator
 NRS: Non-Road Small (SI engines)

Results construction sector 2030

- High spread between different machines in one power class of one sector
→ consideration in possible regulation options



Sensitivity analysis engine categories NRE and NRG

- Influence of factor infrastructure by +/- 25% → low improvement potential

Year	Baseline EP	EP scenario "Infrastructure -"	EP scenario "Infrastructure +"
2030	0.58	0.42	0.61
2050	0.60	0.43	0.64

- Available charging power: base 43 kW (2030) or 80 kW (2050) according to LV mobile grid connection
 - scenario "-": 11 kW (2030) or 20 kW (2050)
 - scenario "+": improvement by 20 %

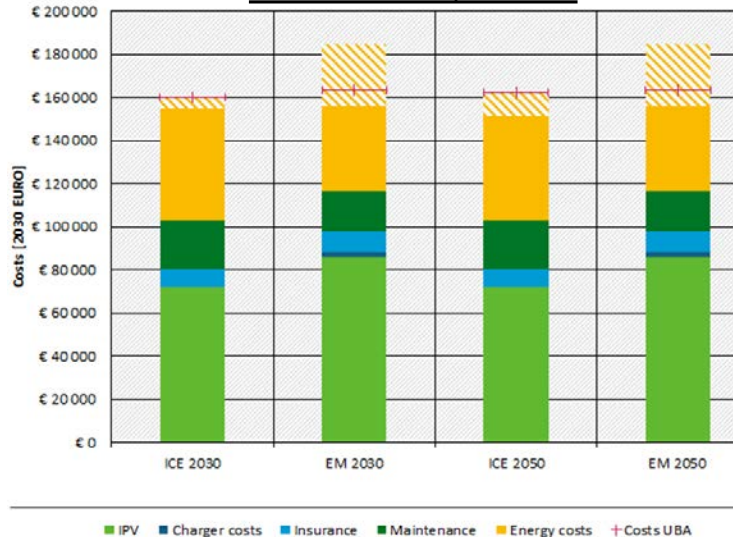
Year	Baseline EP	EP scenario "Charging -"	EP scenario "Charging +"
2030	0.58	0.40	0.59
2050	0.60	0.49	0.60

- Improved battery technology → low improvement potential
- Adopted user behaviour → low improvement potential
- Factor special solution → low effect since the factor is not applied to all machine categories

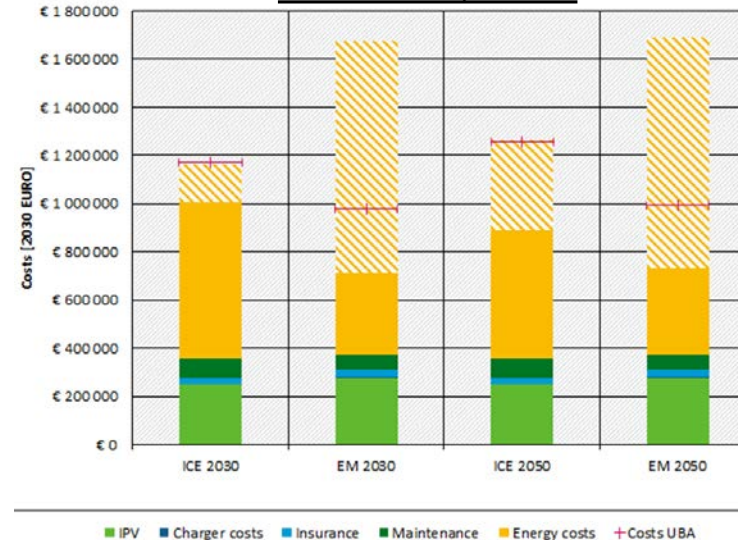
TCO analysis for mini excavator, crawler excavator and wheel loader

- Depreciation period is 7 years without battery change in this time frame
- High impact of energy costs, especially for high-powered machines
 - Electrified machines could be the better solution, but high uncertainty in price development

Mini excavator, 14.8 kW



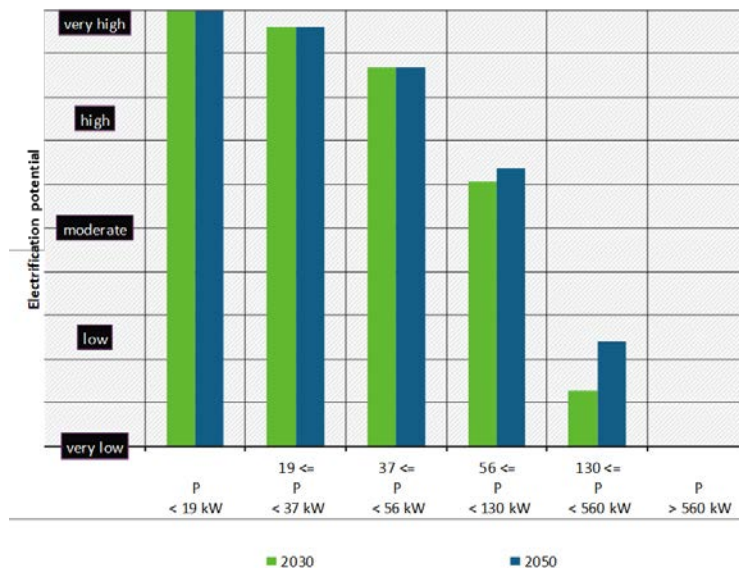
Wheel loader, 228 kW



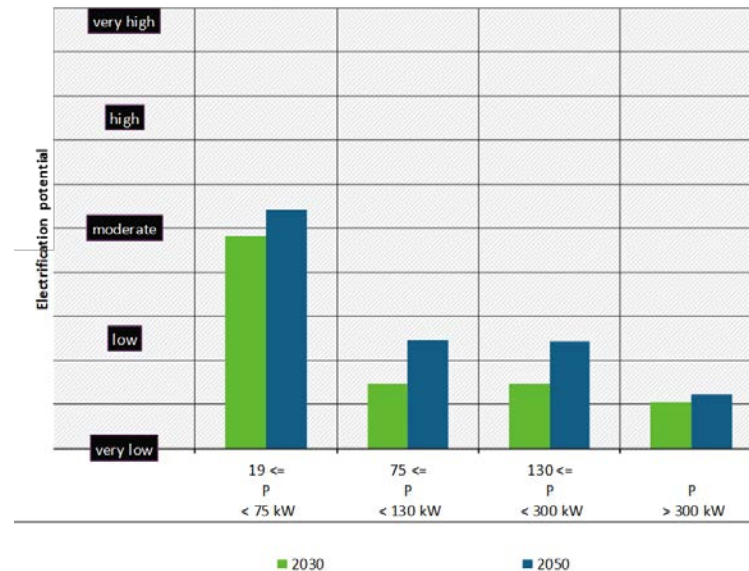
Results construction machinery and shipping

- Decreasing electrification potential with increasing engine power
- Improvement from 2030 to 2050 limited

Construction machinery

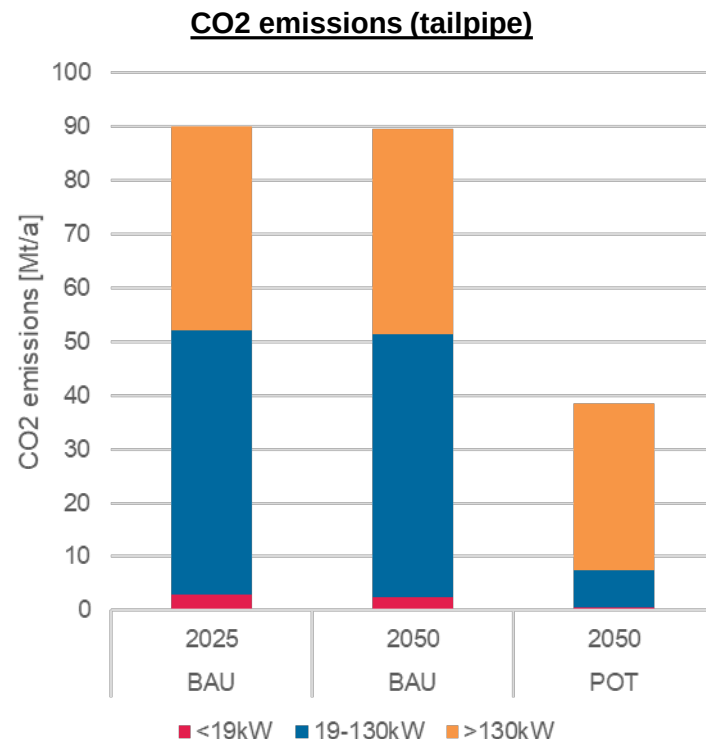


Inland waterway shipping



Scenario analysis – all NRMM sectors

- BAU scenario
 - No CO₂ regulation
 - Low motivation for using the electrification potential
- POT scenario
 - Adaption of calculated electrification potentials
 - No coverage of all CO₂ emissions by electrification



BAU: Business as usual

POT: electrification potential fully used