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Estimating the Global Emissions by Fluid Power Machinery

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Abstract.

Faced with the ongoing climate crisis and increased regulatory focus on emission reductions, it is especially relevant to identify key loss mechanisms across industries, responsible for energy consumption and associated emissions not producing any work. Minimizing losses may directly and significantly reduce emissions, fossil fuel dependence, the need for new renewable energy sources , and potential changes to the electric grid. Given the principal losses associated with many fluid power systems, fluid power machinery sectors are likely a source of high emissions when compared to emissions on a global scale. Therefore, this study aims to estimate the global emissions by fluid power machinery. Literature on this topic is generally fragmented, and the most recent and most exhaustive study on this subject was conducted for the United States in 2012, which encompassed both mobile hydraulic, industrial hydraulic, pneumatic, and aviation industries. This 2012 survey was conducted by the Oak Ridge National Laboratory in collaboration with the National Fluid Power Association and major U.S. and European-based industry players. Combining these 2012 findings with global emissions by relevant industries, such as construction machinery and energy production, this paper estimates the global emissions by fluid power machinery, sans aviation hydraulics; these are then grouped according to hydraulic mobile machinery, hydraulic industrial machinery, and pneumatic machinery. The estimation results suggest emissions by fluid power machinery exceed twice that of global aviation, amounting to roughly 5% of the global energy-related emissions. The findings of this study present a novel state-of-the-art assessment of the global CO_2 emissions generated by this sector. Finally, it suggests remarkable potential among multiple decarbonization pathways.

Keywords. Fluid Power Machinery, Energy Consumption, Emissions, Sustainability.

1. Introduction

Fluid power is a means of power transmission through pressurized working fluids. It includes hydraulics, using liquid as the working fluid, and pneumatics using air/gas as the working fluid, and plays a vital role in modern machinery, automation and transportation. Fluid power technologies are indispensable in applications demanding high power and/or force density, precision and reliability. Fields of application are virtually countless and Fig. 1.1. illustrates a few examples of the wide application range where fluid power technologies are key enablers, emphasizing its broad versatility and vital role in modern technology.

Figure 1.1. Examples of machinery where fluid power is indispensable.

Fluid power technologies improve resilience, functionality and productivity across industries. An example known to many people is an excavator as shown in Fig. 1.2., where fluid power is an indispensable enabler for its functionality.

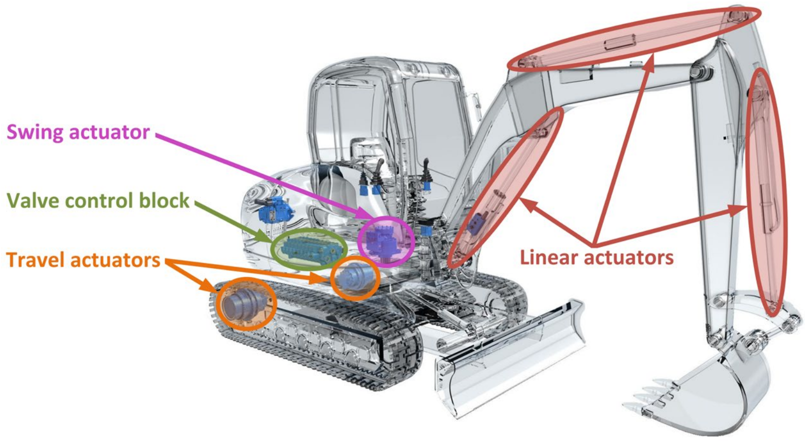

Figure 1.2. Examples of indispensable functions in an excavator enabled by fluid power.

Facing climate change, key challenges for fluid power technology include low system level energy efficiencies, resulting in excessive energy use and associated emissions. Whereas todays fluid power components are rather efficient, system level working principles have largely remained unchanged for decades. To unlock the decarbonization potential of fluid power technologies, energy efficient fluid power system architectures must be at the heart of research efforts, enabling competitive and sustainable technologies.

1.1. Starting Point for Emission Estimates

Studies related to emissions by fluid power machinery in literature is generally fragmented and often related to single machines, single machine categories and so forth, see e.g. [15-18, 26]. The most recent and most exhaustive study on this subject was conducted in 2012 for the U.S. encompassing both mobile hydraulic, industrial hydraulic, pneumatic and aviation industries [1]. The study was conducted by the Oak Ridge National Laboratory in collaboration with the U.S. National Fluid Power Association (NFPA) and 31 industrial partners, including major technology players in both manufacturing as well as OEMs such as Bosch Rexroth, Danfoss, Festo, Poclain Hydraulics, ABB, Siemens, Parker Hannifin, Caterpillar and Sun Hydraulics. The study was targeting the collection and consolidation of specific measurements related to energy consumption, associated emissions and energy efficiencies of deployed fluid power systems [1]. In this context the results may be considered the most broad and trustworthy information on the subject available and is hence used as a reference case for estimating the global emissions by fluid power machinery. As the primary aim here is to estimate the emissions related to mobile and industrial hydraulic and pneumatic machinery, the findings related to aviation in [1] are left out in the following.

1.2. Considerations & Assumptions Applied

The study presented in this paper aims to estimate the global emissions by fluid power machinery in a 2022 scenario, with the reason for this specific year being reference availability. The emission estimates presented uses the 2012 U.S. energy consumption and emission estimates by fluid power machinery [1] as a reference, taking offset in the energy consumption reported here. A main difference from [1] is the emissions by electric energy generation, which generally was lower in 2022 compared to 2012, partly due to a different mix of energy sources, both in the U.S., and globally. Hence, the choices of the emissions per energy unit used in both the 2012 U.S. reference case and the 2022 scenario are considered below for clarity. Note that "CO_2" in the following refers to CO_2 equivalents.

1.2.1. Emissions Related to Diesel Fuel Consumption

Mobile hydraulic machinery remains predominantly powered by internal combustion engines (ICEs) using diesel fuel. According to [1], the emissions per energy unit is equal to 0.249 MMT CO_2/TWh (73 MMT CO_2/Quad), which is in close correspondence with estimates obtainable via other sources, e.g. [5-8]. For this reason, both the 2012 U.S. reference case and the 2022 global emissions scenario uses 0.249 MMT CO_2/TWh for ICE powered fluid power machinery, not accounting for the emissions related to production of the fuel itself.

1.2.2. Emissions Related to Electric Energy Generation

Industrial hydraulic and pneumatic machines are generally electrically powered, and compared to the 2012 study [1], the 2022 emissions/electric energy unit are much different both in the U.S. and globally. The 2012 estimate for the U.S. in [1] suggests emissions related to electric energy generation to be 0.607 MMT CO_2/TWh (178 MMT CO_2/Quad). According to [3], the average 2022 emissions/electric energy unit were for example:

- 0.586 kg CO_2/kWh in China [3]
- 0.292 kg CO_2/kWh in the EU [3]
- 0.386 kg CO_2/kWh in the U.S. [3]
- 0.486 kg CO_2/kWh globally [3]

In addition, [2] suggests that emissions from electric energy generation in the EU in 2022 were even lower than the estimate of [3], namely with emissions of 0.258 kg CO_2/kWh. To be conservative in the emission estimates the 2022 EU emissions per electric energy unit generated as presented in [3] are assumed globally valid.

In addition, it is notable that the emissions per electric energy unit = 0.258 kg CO_2/kWh = 0.258 MMT CO_2/TWh [3] is only 3.6 % higher than the emissions per diesel energy unit = 0.249 MMT CO_2/TWh [1]. Hence, for conservativeness and transparency, **the 2022 global emission estimates assumes that emissions per electric energy unit are identical to those of diesel fuel**, i.e. = 0.249 MMT CO_2/TWh.

1.2.3. Relative Impact of Emissions in the Context of Efficiency

Considering especially the emissions per electric energy unit presented in [1], with 0.607 MMT CO_2/TWh and 0.249 MMT CO_2/TWh for diesel energy, it may seem like diesel fuel being the preferred choice if emissions should be as low as possible. However, here the energy efficiency plays a significant role, with this being highly dependent on the load conditions. As discussed in section 3.2. in the following, the average efficiency of ICEs and electric systems (prime movers) can be assumed to be 45% and 90%, respectively. In this case an ICE producing 1.0 unit of mechanical energy at the output shaft would require 2.2 units of fuel energy, whereas an electric motor/drive unit would require 1.1 units of electric energy to produce 1.0 unit of mechanical energy at the shaft.

Using the emissions per energy unit presented in [1], the corresponding emissions related to producing 1.0 TWh on the shaft would be 0.55 MMT CO_2 for an ICE, and 0.67 MMT CO_2 for an electric motor/drive unit, suggesting that ICE powered machinery emits less CO_2 than electric powered machinery in the 2012 U.S. reference case.

However, whereas emissions by diesel fuel remains the same, the 2022 emissions related to electric energy in the EU was 0.258 MMT CO_2/TWh as discussed in section 1.2.2. Using this measure, and an electric motor/drive unit producing 1.0 TWh on the shaft would emit 0.29 MMT CO_2, corresponding to 53% of the emissions by ICEs with the same output.

It is notable that with an increasing implementation of renewable energy sources, the emissions associated with electric powered machinery will decrease, whereas it for ICE powered machinery will stay the same, assuming fluid power system efficiencies unaltered.

1.2.4. Summary of Emissions per Energy Unit used in the Study

From the considerations above the emissions per energy unit used in the 2012 reference case and the assumed emissions per energy unit for the 2022 global emission scenario, are summarized below for clarity.

2012 reference case for the U.S. emissions by fluid power machinery

- 0.249 MMT CO_2/TWh for diesel energy
- 0.607 MMT CO_2/TWh for electric energy

2022 global emission scenario for fluid power machinery

- 0.249 MMT CO_2/TWh for diesel energy
- 0.249 MMT CO_2/TWh for electric energy

The emissions per energy unit used in the 2022 global emission estimates are indeed conservative from the considerations above, and likely somewhat higher.

Finally, from the above considerations and assumptions as well as the limited sources available, the estimated emissions by fluid power machinery cannot be considered subject to scientific rigour, but rather *best estimates*.

2. ENERGY USE & EMISSIONS BY FLUID POWER MACHINES – THE 2012 U.S. REFERENCE CASE

Following [1], the energy consumption by fluid power machinery in the U.S. in 2012 are summarized in Table 1. For mobile fluid power machinery, the maximum TWh/year measures for *Construction machinery*, *Agriculture machinery* and *Other mobile machinery* are extrapolated from their minimum values using the ratio of maximum and minimum TWh/year for *Total mobile hydraulic machinery* in Table 1.

As the maximum and minimum energy consumption covers estimate ranges, it is assumed that the **average of the minimum and maximum values is representative for the *actual* energy consumption** as specified in Table 1. From this assumption, the % distribution of energy consumption of fluid power machinery is obtained as also specified in Table 1.

Table 1: Energy consumption estimates by fluid power machinery in the US in 2012. Numbers in **bold** font are obtained or directly deduced from [1] and converted from Quads to TWh. Remaining numbers are own calculations.

2012 US Energy Consumption by Fluid Power Machinery	Minimum TWh/yr	Maximum TWh/yr	Avg. TWh/yr	% Avg. TWh/yr
Mobile hydraulic machinery				
- Construction machinery	**68.3**	237.7	153.0	21.7
- Agriculture machinery	**4.7**	16.3	10.5	1.5
- Other mobile machinery	**33.1**	115.3	74.2	10.5
Total mobile hydraulic machinery	**106.1**	**369.3**		
Total industrial hydraulic machinery	**321.2**	**321.2**	321.2	45.5
Total pneumatic machinery	**146.5**	**146.5**	146.5	20.8
Total	**573.8**	**837.0**	705.4	100.0

The estimated CO_2 emissions associated with the energy consumption measures in Table 1 are outlined in Table 2. Here the estimated CO_2 emissions for mobile hydraulic machines are estimated from using 0.249 kg CO_2/kWh = 0.249 MMT CO_2/TWh. As discussed, industrial hydraulic and pneumatic machines are primarily electrically powered, and [1] suggests related emissions of approximately 0.607 MMT CO_2/TWh in 2012 as discussed in section 1.2. Applying these emissions/energy unit measures, the corresponding emissions in Table 2 are obtained, which are nearly identical to the estimates presented in [1].

Table 2: 2012 emission estimates by fluid power machines in the US deduced from [1].

2012 US Emissions by Fluid Power Machinery	Minimum MMT CO_2/yr	Maximum MMT CO_2/yr	Avg. MMT CO_2/yr	% Avg. CO_2/yr
Mobile hydraulic machinery (diesel)				
- Construction machinery	17.0	59.1	38.0	11.1
- Agriculture machinery	1.2	4.1	2.6	0.8
- Other mobile machinery	8.2	28.7	18.4	5.4
Total mobile machinery	26.4	91.8		
Total industrial hydraulic machinery	195.1	195,1	195.1	56.8
Total pneumatic machinery	89.0	89.0	89.0	25.9
Total	310.5	375.9	343.2	100.0

3. GLOBAL EMISSION ESTIMATES BY FLUID POWER MACHINERY – A 2022 SCENARIO

Fluid power system technologies remain virtually unaltered since 2012, i.e. primarily related to throttle control. Similarly mobile hydraulic machines remain primarily powered by diesel fuelled ICEs, and industrial hydraulic and pneumatic systems remain predominantly electrically powered. It has not been possible to account for the % distribution of deployed fluid power machines in different geographic regions. Hence, for conservativeness, the following assumes that the percentage distribution of mobile hydraulic, industrial hydraulic and pneumatic machinery outlined in Table 1 is valid globally.

In 2022, [9] reported that global emissions by construction machines amounted to 400 MMT CO_2/year, a number that has been referenced in several publications, e.g. [10-13]. Applying this measure, the assumptions from section 1.2.4, and the % energy consumption by construction machines in Table 1, emissions are estimated to 18.44 MMT CO_2/ % energy consumption. From this, the global emissions are estimated as in Table 3.

Table 3: Global CO_2 emission estimates by fluid power machines.

Global CO_2 Emission Estimates based on average US Energy % Distribution	% Average TWh/yr	Average MMT CO_2/yr
Mobile hydraulic machinery (diesel)		
- Construction machinery	21.7	400.0
- Agriculture machinery	1.5	27.5
- Other mobile machinery	10.5	194.0
Total mobile machinery		621.5
Total industrial hydraulic machinery	45.5	839.9
Total pneumatic machinery	20.8	383.1
Total	100.0	1,844.5

3.1. Emission Impact of Fluid Power Machinery

To put the estimated emissions by fluid power machinery in perspective, these are compared to the much-scolded aviation sector and the global energy related emissions.

In 2022 international aviation was estimated to be responsible for emitting approximately 800 MMT CO_2/year [14], distributed by 331 MMT CO_2/year for domestic aviation and 470 MMT CO_2/year for international aviation. In comparison fluid power machinery is the same year estimated to emit 2.3 times more than global aviation.

Similarly, the 2022 global energy related emissions are estimated to 36,800 MMT CO_2/year [2], hence the total emission estimate above suggests that fluid power machinery was responsible for 5% of the global energy related emissions.

3.2. Emissions of Fluid Power Machinery related to Losses & Useful Work

Having established the significant emission impact of fluid power machinery, the following aims to quantify which part of emissions that are related to prime mover losses, fluid power system losses and useful work. To investigate this, the average efficiencies related to fluid power machinery segments proposed in [1] are used. Considering the portion of energy use related to mobile hydraulic, industrial hydraulic and pneumatic machinery when combined with the respective average efficiencies, the weighted efficiencies in Table 4 are obtained.

Table 4: Weighted energy efficiencies based on percentage energy use.

Fluid Power Machinery	% Average TWh/yr	Average Energy Efficiency in % [1]	Weighted Efficiency
Mobile hydraulic machinery (diesel)	33.7	**21**	7.1
Total industrial hydraulic machinery	45.5	**50**	22.8
Total pneumatic machinery	20.8	**15**	3.1
Total	100.0		33.0

From Table 4 the overall weighted efficiency of fluid power machinery is found to 33%, meaning that 67% is lost in power transmission processes. Considering now the underlying efficiencies, several reports suggest ICE brake thermal efficiencies in ranges 42-43% [22], 43-44% [23] and 45–46% [24]. Similarly, total efficiencies electric motor plus electric drives and wiring have been estimated to 88.0% [19], 89.8% [20] and [21] suggest efficiencies in the range 80-90%, which is supported by the findings in e.g. [25]. Based on this, the following assumes an average fuel-to-shaft efficiency for ICEs of 45% and an average grid-to-shaft efficiency for electric prime movers of 90%.

Table 5: Energy efficiency estimates on machine subsystem level.

Fluid Power Machinery	ICE/Electric Subsystem Efficiency in %	Hydraulic/Pneumatic Subsystem Efficiency in %	Total Efficiency
Mobile hydraulic machinery	45	47	21
Industrial hydraulic machinery	90	56	50
Pneumatic machinery	90	17	15

Based on these *prime mover* efficiencies the hydraulic and pneumatic (sub)system efficiencies outlined in Table 5 are obtained, such that the total machine efficiencies are in correspondence with those specified in [1]. Hence, these efficiency estimates are used to estimate the associated emissions. Defining energy consumption as the input energy E_{in}, the output energy of a prime mover (ICE or electric) as E_{pm} and the output energy of a fluid power systems E_{fp}, the energy flow in fluid power machinery may be depicted as in Fig. 3.1.

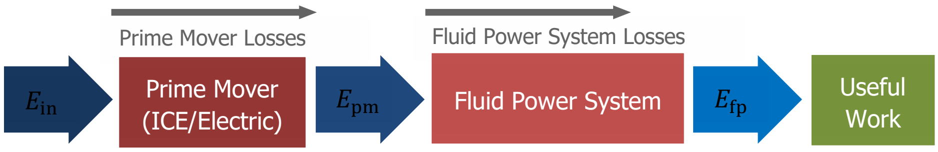

Figure 3.1. Energy flow in fluid power machinery.

Furthermore, defining the prime mover and fluid power system efficiencies as η_{pm} and η_{fp}, respectively, the prime mover losses $E_{\text{pm,loss}}$, fluid power system losses $E_{\text{fp,loss}}$ and useful work E_{uw} may be obtained through Eqs. (3.1)-(3.4).

$$E_{\text{pm}} = \eta_{\text{pm}} E_{\text{in}} \quad , \quad E_{\text{fp}} = \eta_{\text{fp}} E_{\text{pm}} = \eta_{\text{fp}} \eta_{\text{pm}} E_{\text{in}} \tag{3.1}$$

$$E_{\text{pm,loss}} = E_{\text{in}} - E_{\text{pm}} = (1 - \eta_{\text{pm}}) E_{\text{in}} \tag{3.2}$$

$$E_{\text{fp,loss}} = E_{\text{pm}} - E_{\text{fp}} = \eta_{\text{pm}} E_{\text{in}} - \eta_{\text{fp}} E_{\text{pm}} = (1 - \eta_{\text{fp}}) \eta_{\text{pm}} E_{\text{in}} \tag{3.3}$$

$$E_{\text{uw}} = E_{\text{in}} - E_{\text{pm,loss}} - E_{\text{fp,loss}} = \eta_{\text{fp}} \eta_{\text{pm}} E_{\text{in}} \tag{3.4}$$

Noting that emissions/energy unit are assumed identical for diesel and electric powered machinery as discussed in section 1.2., the emissions may be considered proportional to the associated energy consumption. Hence, prime mover loss related emissions $\varepsilon_{\text{pm,loss}}$, fluid power system loss related emissions $\varepsilon_{\text{fp,loss}}$ and the emissions related to useful work ε_{uw}, may be estimated like the associated energy losses Eqs. (3.4), as Eqs. (3.5).

$$\varepsilon_{\text{pm,loss}} = (1 - \eta_{\text{pm}}) \varepsilon_{\text{in}} \ , \ \varepsilon_{\text{fp,loss}} = (1 - \eta_{\text{fp}}) \eta_{\text{pm}} \varepsilon_{\text{in}} \ , \ \varepsilon_{\text{uw}} = \eta_{\text{fp}} \eta_{\text{pm}} \varepsilon_{\text{in}} \tag{3.5}$$

Using the global emission estimates in Table 3, the efficiency estimates in Table 5 and Eqs. (3.5), emissions related to prime mover losses, fluid power system losses and useful work appear as depicted in Table 6.

Table 6: Emission estimates on machine subsystem level.

Emissions related to losses and useful work	Mobile hydraulic machinery in MMT CO_2/yr	Ind. hydraulic machinery in MMT CO_2/yr	Pneumatic machinery in MMT CO_2/yr	Total
Emissions related to ICE/electric subsystem losses	341.8	84.0	38.3	464.1
Emissions related to fluid power subsystem losses	148.2	332.6	286.2	767.0
Emissions related useful work	131.4	423.3	58.6	613.3
Total	621.5	839.9	383.1	**1,844.5**

Due to the proportionality assumption of energy consumption and emissions across machine types, 33% of the emissions are related to useful work, corresponding to the weighted energy efficiency as expected. Furthermore, 25% is associated with ICE/electric system losses and 42% is associated with losses in fluid power systems.

4. DECARBONIZATION PATHWAYS & PERSPECTIVES

From the distribution of emissions related to losses and useful work estimated above, it is evident that there is a significant emission reduction potential for fluid power machinery. Indeed, if all electric energy was generated by renewable energy sources like wind turbines and solar panels, the emission reduction potential would be related to electrification of mobile fluid power machines alone. However, a broadly electrified world will likely not be a reality for decades. In any case, the use of electric energy should be reduced as much as possible to limit the requirement for renewable energy sources, rare earth materials, allow for realistic and commercially feasible battery sizes in mobile machinery etc. Hence, the increase of energy efficiencies to reduce energy consumption should be at the core of future research, development and innovation efforts.

To evaluate the emission reduction potentials by increased energy efficiencies and electrification viewed in a 2022 context as the for the above estimates, Eqs. (4.1)-(4.4) are applied taking offset in useful work, E_{uw}, and hence the reverse calculation process compared to Eqs. (3.1)-(3.4).

$$E_{\mathrm{fp}} = \frac{E_{\mathrm{uw}}}{\eta_{\mathrm{fp}}} \quad , \quad E_{\mathrm{pm}} = \frac{E_{\mathrm{fp}}}{\eta_{\mathrm{pm}}} = \frac{E_{\mathrm{uw}}}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} \tag{4.1}$$

$$E_{\mathrm{fp,loss}} = \frac{E_{\mathrm{uw}}}{\eta_{\mathrm{fp}}} - E_{\mathrm{uw}} = \frac{1-\eta_{\mathrm{fp}}}{\eta_{\mathrm{fp}}} E_{\mathrm{uw}} \tag{4.2}$$

$$E_{\mathrm{pm,loss}} = \frac{E_{\mathrm{fp}}}{\eta_{\mathrm{pm}}} - E_{\mathrm{fp}} = \frac{E_{\mathrm{uw}}}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} - \frac{E_{\mathrm{uw}}}{\eta_{\mathrm{fp}}} = \frac{1-\eta_{\mathrm{pm}}}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} E_{\mathrm{uw}} \tag{4.3}$$

$$E_{\mathrm{in}} = E_{\mathrm{uw}} + E_{\mathrm{pm,loss}} + E_{\mathrm{fp,loss}} = \left(1 + \frac{1-\eta_{\mathrm{pm}}}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} + \frac{1-\eta_{\mathrm{fp}}}{\eta_{\mathrm{fp}}}\right) E_{\mathrm{uw}} = \frac{1}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} E_{\mathrm{uw}} \tag{4.4}$$

Again, noting the assumption that emissions/energy unit are identical for diesel and electric powered machinery (section 1.2), the prime mover loss related emissions $\varepsilon_{\mathrm{pm,loss}}$, the fluid power system loss related emissions $\varepsilon_{\mathrm{fp,loss}}$ and the emissions related to the input energy $\varepsilon_{\mathrm{in}}$ may be estimated as Eqs. (4.5).

$$\varepsilon_{\mathrm{fp,loss}} = \frac{1-\eta_{\mathrm{fp}}}{\eta_{\mathrm{fp}}} \varepsilon_{\mathrm{uw}} \ , \varepsilon_{\mathrm{pm,loss}} = \frac{1-\eta_{\mathrm{pm}}}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} \varepsilon_{\mathrm{uw}} \ , \varepsilon_{\mathrm{in}} = \frac{1}{\eta_{\mathrm{pm}}\eta_{\mathrm{fp}}} \varepsilon_{\mathrm{uw}} \tag{4.5}$$

The emission estimates presented in the following are hence based on Eqs. (4.5).

4.1. Emission Reduction Potential of Fully Electrified Fluid Power Machinery

As previously discussed, industrial hydraulic and pneumatic machines are already largely electrified [1], hence the main emission reduction potentials of electrification are related to mobile hydraulic machinery. These machines remain predominantly powered by ICEs, however the process of electrifying these is ongoing with a the main focus being the replacement of ICEs by battery powered electric motors and drives, while hydraulic systems remain based of traditional design principles[1]. Hence, following the current trends described, assuming that electrification of such machinery increases the prime mover efficiencies from an average of 45% (Table 5) to an average of 90%, and using Eqs. (4.5.), the emissions appear as in Table 7 for a full electrification of mobile hydraulic machinery.

Table 7: Emission estimates on machine subsystem levels assuming full electrification of fluid power machinery.

Emissions related to losses and useful work	Mobile hydraulic machinery in MMT CO_2/yr	Ind. hydraulic machinery in MMT CO_2/yr	Pneumatic machinery in MMT CO_2/yr	Total
Emissions related to ICE/electric subsystem losses	31.1	84.0	38.3	153.4
Emissions related to fluid power subsystem losses	148.2	332.6	286.2	767.0
Emissions related useful work	131.4	423.3	58.6	613.3
Total	310.7	839.9	383.1	**1,533.7**

Table 7 suggests that a full electrification of fluid power machinery, in a 2022 scenario, would reduce emissions from 1,844.5 MMT CO_2/year to 1,533.7 MMT CO_2/year, amounting to approximately a 17% emission reduction for fluid power machinery.

4.2. Emission Reduction Potential by 50% Fluid Power System Efficiency Increase

Consider now the case of broadly increasing the energy efficiency of fluid power systems with prime mover efficiencies remaining the same as in Table 5. Various works have been reported in literature in the past decades comprising more efficient component designs and especially novel system architectures that reduces conceptual losses, increases energy recuperation capabilities etc. Such developments suggest that energy efficiencies may be significantly increased. It is difficult to establish the exact energy efficiency potential, however, in view of the mentioned development the authors believe that a 50% increase in fluid power system efficiencies is achievable on the average. Using this measure and Eqs. (4.5), the emission estimates for fluid power machinery appears as outlined in Table 8.

While the assumed efficiency increase reduces the energy consumption and the associated emissions related to fluid power systems, the reduced fluid power system losses also reduce the energy throughput of the prime movers, hence the prime mover energy losses and emissions. The results in Table 8 suggest that a 50% increase in fluid power system efficiencies would result emission reductions from 1,844.5 MMT CO_2/year to 1,229.6 MMT CO_2/year, i.e. a reduction of 614.9 MMT CO_2/year corresponding to 33.3%.

It is notable that the emission reduction potential of broadly increasing energy efficiencies in fluid power systems by 50%, is roughly twice that of fully electrifying fluid power machinery while maintaining traditional hydraulic system architectures. This emphasizes the necessity of the fluid power research community and industry to focus on research and development of more efficient components and especially system architectures.

[1] Experiences by the authors at BAUMA fairs in 2022 and 2025 in Munich, Germany.

Table 8: Emission estimates on machine subsystem levels assuming a 50% efficiency increase in all three fluid power machinery groups.

Emissions related to losses and useful work	Mobile hydraulic machinery in MMT CO_2/yr	Ind. hydraulic machinery in MMT CO_2/yr	Pneumatic machinery in MMT CO_2/yr	Total
Emissions related to ICE/electric subsystem losses	227.9	56.0	25.5	309.4
Emissions related to fluid power subsystem losses	55.0	80.6	171.3	306.9
Emissions related useful work	131.4	423.3	58.6	613.3
Total	414.3	559.9	225.4	**1,229.6**

4.3. Emission Reduction Potential of a 50% Efficiency Increase & Electrification

Having considered the emission reduction potentials separately related to a full electrification of fluid power machinery and to a 50% increase in fluid power system efficiencies, the impact of doing both is considered.

Applying efficiencies of 90% for both prime mover types, corresponding to fully electrified machinery, and a 50% increase in fluid power system efficiencies to Eqs. (4.5), the emissions presented in Table 9 are obtained.

Table 9: Emission estimates assuming a 50% efficiency increase broadly, and a full electrification of fluid power machinery.

Emissions related to losses and useful work	Mobile hydraulic machinery in MMT CO_2/yr	Ind. hydraulic machinery in MMT CO_2/yr	Pneumatic machinery in MMT CO_2/yr	Total
Emissions related to ICE/electric subsystem losses	20.7	56.0	25.5	102.2
Emissions related to fluid power subsystem losses	55.0	80.6	171.3	306.9
Emissions related useful work	131.4	423.3	58.6	613.3
Total	207.2	559.9	225.4	**1,022.5**

From Table 9 it is found that the emissions may be reduced from 621.5 MMT CO_2/year to 207.2 MMT CO_2/year for mobile hydraulic machinery, from 839.9 MMT CO_2/year to 559.9 MMT CO_2/year for industrial hydraulic machinery and from 383.1 MMT CO_2/year to 225.4 MMT CO_2/year for pneumatic machinery. These reduction measures correspond to 66.7%, 33.3% and 41.2% for mobile hydraulic, industrial hydraulic and pneumatic machinery, respectively.

In total, emissions by fluid power machinery may be reduced from 1,844.5 MMT CO_2/year 1,022.5 MMT CO_2/year corresponding to 44.6%.

5. SUMMARY

A study on the emission reduction potential by fluid power machinery is presented. With offset in previous studies on energy consumption and energy efficiencies of fluid power machinery conducted for the U.S. combined with conservative estimates for emissions by especially electric energy generation and recent emission estimates for construction machinery, the emissions by fluid power machinery are conservatively estimated to approximately 1,844 MMT CO_2/year in a 2022 scenario. It is found that this emission level corresponds to 2.3 times that of global aviation and approximately 5% of the global energy related emissions.

In addition, the emission reduction potentials offered by a full electrification of fluid power machinery, respectively a 50% increase in fluid power system efficiencies, is investigated, as well the combination of a full electrification and a 50% efficiency increase. The results are shown for comparison in Fig. 5.1., emphasizing the significant emission reduction potentials present under these conditions, separately, and combined.

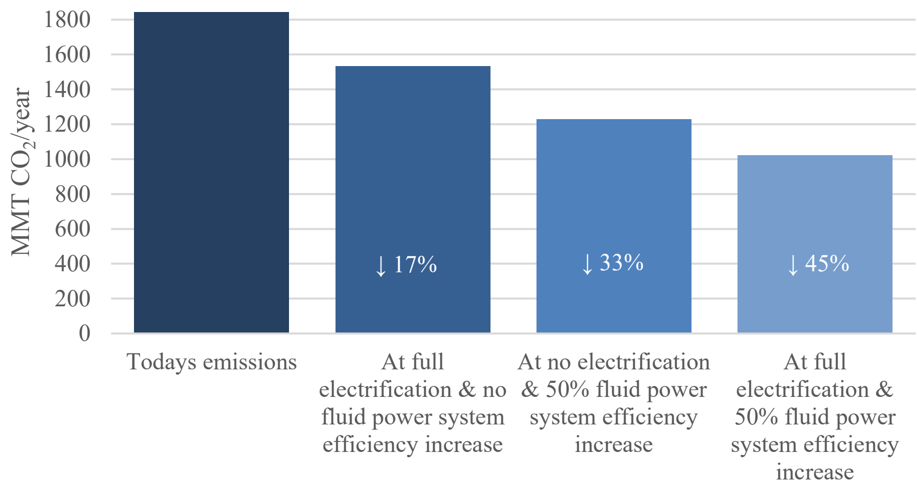

Figure 5.1. Comparison of emission reduction potentials.

In context of the global energy related emissions, the emission reduction potential for a full electrification of fluid power machinery is 0.8%, whereas the emission reduction potential of a 50% fluid power system efficiency increase is a 1.7% reduction in the global emissions. These results emphasize that the emission reduction potentials related to increasing fluid power system energy efficiencies by far exceeds that of electrifying fluid power machinery. However, the potential of a 50% fluid power system efficiency increase and a full electrification has the potential to reduce global emissions by 2.2%. This corresponds to an emission reduction of 822 MMT CO_2/year, exceeding the total emissions by global aviation.

From these estimates of emission reduction potentials, it is found that it is not the electrification of fluid power machinery, which is currently ongoing, that individually possess the largest emission reduction potential, but rather the increase of fluid power system efficiencies. Naturally, however, both increasing system level fluid power efficiencies while electrifying fluid power machinery should be key focus areas for research, development and innovation in the years to come.

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