15th IFK
Proc. of the 15th International Fluid Power Conference

Decarbonization in mobile machinery – from reducing the carbon emissions to emission-free drivetrains

Dr. Andreas Schumacher

Dr. Andreas Schumacher, Danfoss Power Solutions GmbH & CO OHG, aschumacher@danfoss.com

Abstract.

Here in Europe, the carbon emissions of components and machinery are getting more in focus. A lot of regulations are driving this, but also the market demand increases for reduced carbon footprint to also emission-free vehicles. As the use-phase is typically in mobile machinery the by far and outmost the biggest contributor to the CO2-footprint of a machine, reducing energy consumption is key. Significant contributions are coming surely from the typical prime energy source, the engine, but also from the drivetrain as well as the work hydraulics. To reduce the energy consumption of these functions, solutions can be applied with a three-level approach:

- The first level is based on the components.
- The next level is on (sub-)systems and software.
- The last level is on the machine and the prime energy source, where e.g. switching from diesel to battery-electric also leads to significant decarbonization.

The paper will show the impact on all three levels which can be done with Danfoss components in more detail. The potential shown will be backed up with measurement data. So it will become clear, that the journey towards zero emission vehicles is possible, it can start today on these different levels on the machines, also with very high impact on reducing the TCO of a machine as highly efficient components and systems not only reduce the CO2e emissions but also reduce operation costs.

Keywords. Datacenter design, energy efficiency of datacenter, energy efficient metrics, datacenter carbon footprint computation.

1. INTRODUCTION

In the current situation, especially in Europe, the carbon footprint of products and their usage is becoming increasingly important. Several drivers, from the regulatory site, reporting site and application requirements demand the labelling, publishing and reducing of the carbon footprint of products. The publicly funded research project Fluid 4.0 [1] develops methodologies to share among further product information also CO_2-footprint data of products [2].

Reducing carbon footprints is in mobile machinery also important. There are different regulatory drivers, requiring the report of CO_2 emissions during production and usage of components and complete machines, for example as part of the reporting obligations CSR-D/ ESRS, there as part of product or company carbon footprint reporting (PCF and CCF). Another level of reporting the product or company carbon footprint takes place, when a public sustainability commitment has been engaged. Good examples are here commitments with the Science-based Targets Initiative SBTi [3] or the Carbon Disclosure Project CDP [4]. An obvious consequence is when reporting the PCF of a product, that there is an intrinsic motivation of optimizing the footprint, meaning reducing the product emissions.

Another aspect leading to the need to reduce the carbon footprint of mobile machinery becomes imminent if external regulations require reduced emissions in specific application cases. Here, good examples are indoor operations like with areal lifts in buildings or farm machinery in stables. Or if emission reductions are prerequisites for working in specific areas, like construction sites in dense cities, requiring emission-reduced or even emission free machinery and equipment.

And last but not the least, the bigger-picture-based motivation for emission reductions of machinery is based on the aspect of doing the right thing for our climate. Reducing the emission of CO_2 is scientifically proven the right thing to do to limit the progress of climate change. As this applies for all emitting machines – and mobile machines often can reach big sizes with big power needs – improving the emissions of mobile machinery is a smart move for climate change prevention.

All these motivations to reduce the carbon footprint of a mobile machinery have the same baselining challenge: Where to start and what is an effective way to reduce emissions, especially in the use phase with all the challenges to determine use-phase emissions [5] ?

2. POWER AND LOSSES IN A TYPICAL HYDROSTATIC DRIVETRAIN

For gaining an inside of what impact the different components in typical mobile machinery drives have, the example of a standard hydrostatic drivetrain is being analyzed. **Figure 1** depicts such a drivetrain in a Sankey diagram, which is here, to represent the most common standard architecture, energized by a combustion engine, typically a diesel engine. The power of the engine as prime mover is distributed to the work functions (not shown in that figure) and to the drivetrain, represented with the hydraulic pump and motor to form the hydrostatic transmission. The transmission supplies the power via a gearbox to the wheels. For the sake of simplification, the wheels are not represented in Figure 1, so the usable energy to propel the machine is emitted at the gearbox, here.

Figure 1 also includes typical maximum efficiency values for the components in the drivetrain, starting from the engine with around 40% total efficiency in best points. With these given values, assuming all components are operated in their best points, from 100 *kW* input power only nearly 35 *kW* are usable at the gearbox output.

It also needs to be considered, that the maximum efficiencies are listed in Figure 1. That means, in other words, in normal operations, when engine and hydrostatic transmission dynamically sweep through their operation and efficiency maps, lower component and system efficiencies are very likely.

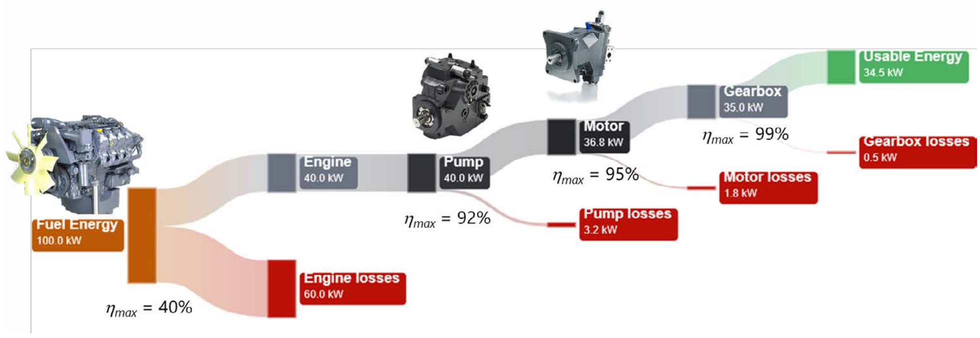

Figure 1: Power- and loss-flow in a standard hydrostatic drivetrain

Based on the illustrative losses of the individual components, Figure 1 makes it clear that going from engine to the wheels has the biggest impact, gaining reductions, but that is also the most complex path from the change-perspective. Hence, depending on the target one has in decarbonization, swapping the prime energy supply might lead to too complex solutions to begin with, especially taking into account that for some bigger mobile machinery the energy demand for a regular working day exceeds what alternative decarbonized energy sources can deliver, like batteries or hydrogen H_2. Their storage would become way too big to support the equivalent energy supply to diesel fuel.

Thus, it is very reasonable to analyze from wheels to the engine, excluding the gearbox and start with the hydrostatic motor. This also gives an estimation of what level of change is sufficient to realize the sought decarbonization level in the drivetrain.

3. DECARBONIZATION ON COMPONENT LEVEL

Starting the impact analysis as mentioned with a hydraulic motor, to derive a better understanding of what is the impact in efficiency and CO_2-emissions, two different types of hydraulic motors used in transmissions will be discussed in this chapter. A typical configuration of a hydrostatic transmission consists of a variable displacement pump in axial piston design paired up with a fixed motor.

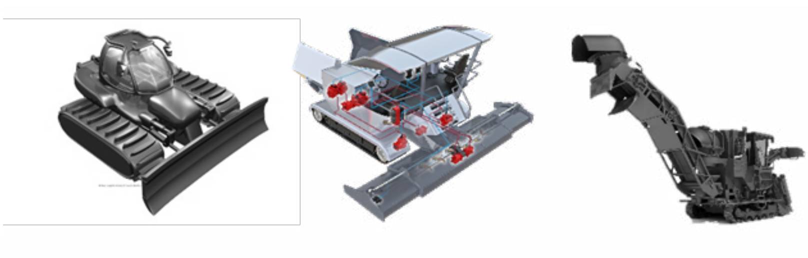

Figure 2: Power and loss-flow in a hydrostatic drivetrain [Source right image: Internet]

This configuration is often used in smaller machines where the cost impact has a high priority or also in more complex machines with a so-called dual path configuration – driving two tracks or wheels in a skid-steering architecture, demonstrated in **Figure 2**. These vehicles are not intended for high speeds and thus operate well with a fixed motor - compared to a variable motor.

To get a fair comparison, the vehicle example used here is a smaller crawler as shown in Figure 2 on the left side. In this setup, the comparison is made between version 1, consisting of a Danfoss S90MF075 swashplate-technology motor with 75 cm^3/rev as the predecessor and a Danfoss H1F080 bent-axis motor with 80 cm^3/rev as the new product with higher efficiency. But just the comparison of the peak efficiency is not giving satisfying information what might be achieved in normal machine operation. To overcome this, two typical operation conditions of the crawler are compared, which are:

- **Working:** Lower speed and high tractive force; approx. 5 *km/h* and ~75 *kN* tractive force. This represents the condition when the crawler moves material by pushing it forward.
- **Transport:** Highest speed and medium tractive force; approx. 13 *km/h* and ~40 *kN* tractive force, representing the machine returning to the starting point after pushing material to continue moving material or relocating to a different location for work.

As this comparison focuses on the impact of motor technology, the pump as well as the further drivetrain components are not shown in this comparison, it will be assumed that the difference in motor displacement is compensated by the gearbox driving the sprocket so that the same speeds and tractive forces are achieved on machine level.

The results of this comparison are shown in the next figure, **Figure 3**, where the resulting advantage of the new H1F is demonstrated in the bar chart of the predecessor-product S90MF. The gray bars are for the S90 motor, the red for the new H1F.

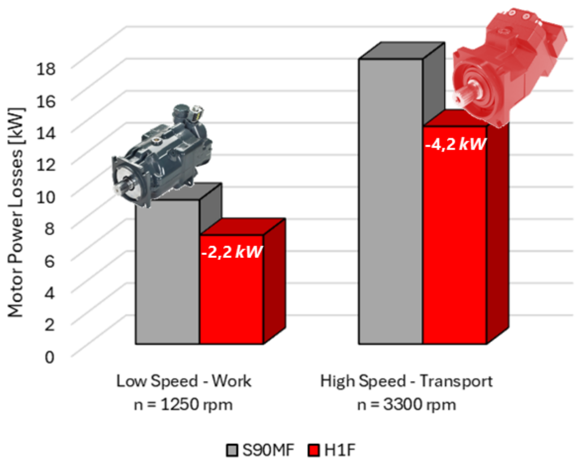

Figure 3: Results of the losses comparison S90 vs H1F-motor in two operation conditions

The diagram shows clearly that the new technology has an impact when analyzed in real operation conditions. The losses for the low-speed working conditions and in the higher-speed conditions are on a similar reduction level close to 25% lesser that using the older product with the swashplate technology – or in other words, the H1F saved 2,2 *kW* in the low-speed and 4,2 *kW* in the high-speed condition. To calculate the impact on the machine's CO_2-footprint, an approximation of the usage of the machine needs to be determined:

- Small Crawler with typical yearly 1000 *hrs* work, 300 *hrs* transport, and 8 *yrs* machine lifetime. That results in typical 10.400 *hrs* total machine lifetime
- In that load cycle, 17,6 *MWh* losses are avoided during Work and 33,6 *MWh* losses avoided in Transport conditions, so 51,2 *MWh* in total.
- Typical diesel engine with 215 *g/kWh* fuel consumption – this value is lower than the best point and thus represents variable load conditions with around 35% engine efficiency.

With these approximations and an emission factor of 2,9 *kg* CO_2e per liter diesel fuel, it can be calculated that the application of an H1F **avoids 38,3 *to* CO_2e** per machine life through a 2% weighted efficiency increase only compared to the S90MF – by just exchanging this single component in a drivetrain.

4. DECARBONIZATION ON SYSTEM LEVEL

If a higher decarbonization level is desired, the system level offers higher reduction potential. System level, that might either comprise of multiple components, making a hydraulic system or it can also take the control software into account. In this chapter, the key element leading to CO_2-reductions is the Danfoss Digital Displacement® Pump DDP. That pump is combining multiple smaller pump units in one housing. The pump units are based on a variable radial piston pump design whereas the variability is achieved by connecting and disconnecting the piston during its stroke to/from the outlet. The pistons of the pump can be actuated all individually, run on different pressure levels and they can also be completely deactivated (not connected), so that Power on Demand is possible without efficiency compromises. **Figure 4** depicts two of these pumps, whereas the left is the single DDP096 and the right is a double pump DDP1X0D. The principle of switchable radial piston design delivers very high efficiency also at part stroke and additionally features very high reaction times in changing the displacement. This allows loading the engine at high levels as stalling can be avoided through quick unloading through the pump.

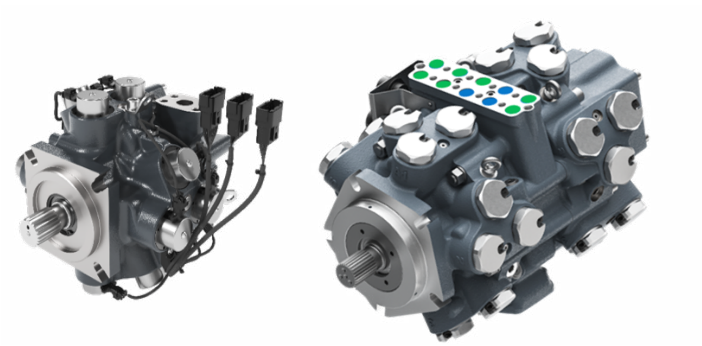

Figure 4: Digital Displacement pump in single (DDP096) and double version (DDP1X0D)

This quick reaction of the pump being applied to an excavator can – with an adapted control software – deliver higher efficiency, as **Figure 5** is explaining. Normally, to prevent the engine from getting overloaded at sudden load-increase situations, the engine is not loaded to its maximum capability, some safety margin is left. That can be avoided with a DDP, the engine can be loaded higher, close to its maximum and thus also operate in areas with higher efficiency.

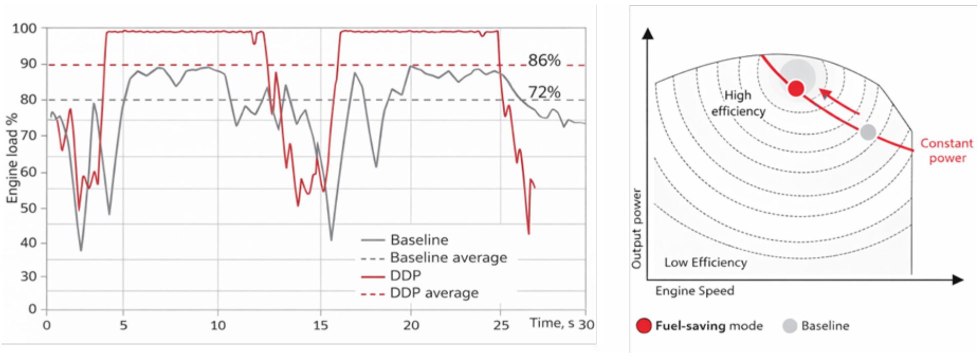

Figure 5: Adapting the control software to the quick reaction characteristics of the DDP

In the left part of Figure 5 the loading of the engine is depicted, in grey the unchanged baseline system with an average loading of 72% of the engine and in red the DDP pump system with adapted control software, where the average load can be increased up to 86%, due to quicker overload prevention. To demonstrate the effect onto the engine, the right diagram is an illustrative example of a fuel consumption shell diagram. The baseline, to reserve some reaction margin through lower loading, operates the engine at lower efficiency conditions (grey point), whereas the optimized system with the DDP moves the operation point of the engine through higher loadings to areas with higher efficiencies. In measurements, published in [6], 21% fuel saving was obtained, although in normal operation conditions, the practical fuel consumption reductions achieve between 10-15%, also dependent on the baseline system design.

The decarbonization potential is further increased when the hydraulic characteristics of the DDP are fully used – the independent use of the different pumping unit outlets. This will now be discussed by taking a classical open-circuit work-function system with a pump, valves and cylinders as an example, like in an excavator boom. In typical hydraulic circuit designs in mobile machinery, an axial piston pump is combined with a proportional valve to actuate the consumer(s). Those systems are typically very prone to throttling losses, especially if multiple consumers with a different flow and pressure demand are supplied simultaneously.

To overcome these conditions, multiple solutions are possible. One is the direct drive of an actuator with a pump, including changing into closed circuit setup, if the drive needs to be reversable. That means, the actuator – a cylinder or motor – is directly coupled to a pump which controls the speed through changing its displacement – aka displacement controlled [7], [8]. Thus, that avoids the valve losses. The downside of this solution is higher installation costs as per consumer one pump is required.

Another solution, which will be discussed here further, is using the characteristics of the DDP. That pump can also be seen as an enhancement of the just described displacement-controlled principle through combining multiple smaller pump units in one housing. The system impact of an installation with these pumps is explained in **Figure 6**, where a classical architecture ("Baseline") on the left is compared with a DDP-architecture on the right ("System Architecture 2").

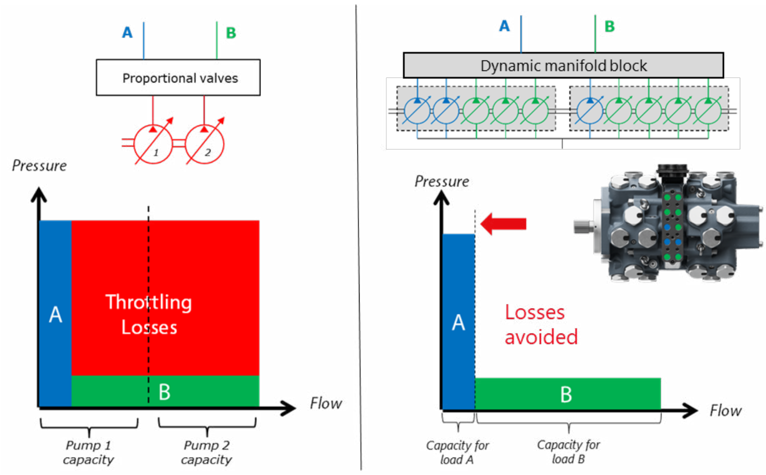

Figure 6: Results of the losses comparison S90 vs H1F-motor in two operation conditions

The baseline system consists of two pumps, delivering flow into a valve block out of which two consumers A and B are supported. The System Architecture 2 uses the double DDP pump with 10 pump units and a dynamic manifold block, out of which the same two consumers A and B are supported. For both systems, the flow and pressure demand is the same, consumer A demands a small flow at a high pressure and B demands a high flow at low pressure. In the classical system, as the flow demand of B is bigger than what only one pump can deliver, both pumps need to be combined and thus run also on the same pressure level – defined by the higher pressure demand from A. For B, the higher pressure needs to be throttled away by the valve block, resulting in the losses indicated by the red area in Figure 6. In the DDP system, with the dynamic manifold, two pistons (blue) will be combined to support the demands of A, the remaining 8 piston suffice the flow demand of B. As the pistons run pressure independently, the throttling losses of the classic system design will be avoided. To estimate and measure the impact of System Architecture 2, [9] has made simulations and tests with an excavator. The outcome is – in short:

- The simulation of a digging cycle delivered that for a classical unchanged **baseline version** of an excavator a typical average **57*kW*** is transmitted from the engine into the hydraulic system (at engine/pump interface).
- The excavator with the **DDP** architecture consumes in same digging cycle **42,3 *kW*** at that pump/engine interface. That is 26% less than the baseline and is composed of a pump loss reduction of 4,4 *kW* (-60%) and 10,5 *kW* in the main control valve (-45%).
- **Measurements** show a realistic fuel consumption reduction of around **25 – 30%** in typical digging cycles. That validates the simulation results well and took also some further reduction potential into account that, due to lower loads, the engine runs in different, more efficient operation conditions.

The fuel saving potential equates roughly with the CO_2-emission reductions, but the detailed impact will be discussed in the next chapter, where also the decarbonization potential of an electrified system will be discussed.

5. DECARBONIZATION POTENTIAL OF E-POWERED MACHINES

Following the system comparison, where "Baseline" is the unmodified standard system of an excavator und "System Architecture 2" in the modified system with a DDP, the next step in analyzing the decarbonization potential is to compare different prime energy sources and their carbon emissions. The natural comparison is a diesel engine to electrification.

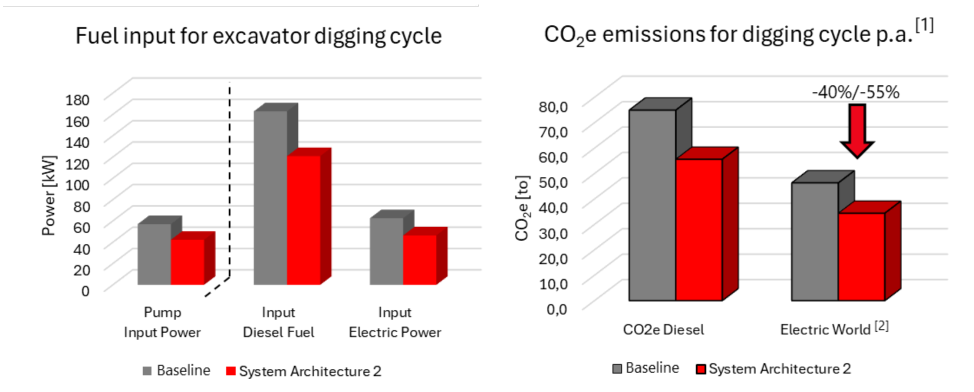

Figure 7: Comparing CO_2 emissions of diesel and electric systems in the excavator [1],[2]

Although there are other fuels available for reducing the CO_2-footprint like HVO, LPG or H_2, the most common alternatives are still diesel and electrification with batteries. Thus, for the above-mentioned excavator, the difference between these both will be further analyzed.

---

[1] Digging cycle per year based on an 8hrs shift and 220 workdays digging
[2] Source of grid emission factors (world/regions): 2024 IEA data

Figure 7 introduces the results of the comparison: Starting on the far-left side with the power at the engine/pump interface, 57 *kW* for the baseline and 42,3 *kW* for the modified system. To be able to realize a CO_2-comparison, the total fuel/electricity consumption needs to be estimated, which is also shown in the left diagram from Figure 7:

- **Diesel:** 163 *kW*/121 *kW* fuel power for Baseline/System Architecture 2 with 215 $^{g}/_{kWh}$ specific fuel consumption or 35% engine efficiency in the digging cycle. Based on this power consumption, System Architecture 2 could save up to 110 *to* CO_2e on a 10.000 *h* machine life.
- **Electric:** 63 *kW*/46 *kW* with using a Danfoss Editron PMI motor with an average 93% and Editron Inverter with an average 98% efficiency during the same cycle (no battery loading/unloading considered here to incorporate cable-powered machines, too)

The highest prime energy and emissions saving can be obtained if the DDP-system is combined with an electric system. The decarbonization potential of electrified systems significantly depends on the electric power generation. The right diagram of Figure 7 depicts that for a diesel engine 75 *to*/56 *to* CO_2e are emitted in a year's time, based on this digging cycle, versus 46 *to*/34 *to* CO_2e for the Baseline and DDP-system with electricity as prime energy – and the CO_2e calculation based on the IEA world grid factors [10]. While the power saving in an electrified System Architecture 2 is approx. $^{2}/_{3}$ over the diesel-driven baseline, the CO_2e emissions are only 55% lower – explained through the power mix in the world grid factors, as that also factors power generation with coal and gas into account. Still, this equates to a machine lifetime saving of around 230 *to* CO_2e in this use case.

The impact of the regional power generation and their CO_2e-factors is shown in **Figure 8**, only for System Architecture 2 (DDP-system).

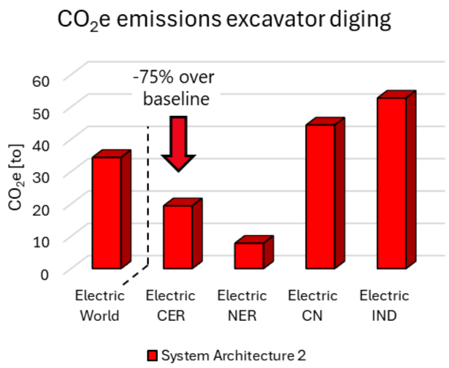

Figure 8: Regional power generation impact of CO_2 emissions

With the world grid emissions equivalent on the far-left side, the other bars in Figure 8 show big the power generation impact is. While in the Northern-European regions NER the renewables in the power generation dominate and thus the CO_2-emissions for the excavator with System Architecture 2 are very small, lower than 10 *to/year*, the same excavator with the same operation cycle would create only 20% less emissions than with a diesel engine in China and nearly the same emissions as a diesel excavator if used in India, as shown in

Figure 7 right part (all with System Architecture 2). This comparison shows that especially in electrification, which is often considered as zero emissions, the emissions during production do have a significant impact on the total emissions of a mobile machine in the use phase. A possibility to capture the information where the machines are used and store for further analyses might be using the emission and energy-reporting functionalities of an Asset Administration Shell, like developed in the Fluid 4.0 project [1].

6. Summary and Conclusions

In this paper, several steps towards decarbonization were discussed and presented, in ascending order of the impact. The smallest impact is achieved if only components of a system will be exchanged to higher efficient components. The example of swapping the S90 fixed swashplate motor to the new H1F bent axis fixed motor delivered in the given application a considerable positive potential of saving up to 10% of CO_2e over the machine lifetime. The next solution discussed is optimizing the system. In the given example, the DDP was the key element. It can contribute with its differentiating characteristics on the one side to a different engine control algorithm, allowing to optimize the engine operation points – accounting up to 25% CO_2e saving potential – and on top of that, on the other side, it allows a redesign in the hydraulic system which especially pays off in valve-based work function systems by reducing throttling losses. This would account for an additional efficiency increase in best case up to 30% in a typical excavator system.

If, in a possible last step, the diesel engine will be replaced by a battery-electric system, the impact is potentially even higher as electric systems have in a broad cycle average 90% efficiency to convert the electric energy into mechanical energy, where the engine efficiency is around 40% – only in its best point and in part-load conditions significantly worse. Nonetheless, an additional factor to determine the CO_2-footprint impact is how the electricity used is generated. In a worst-case scenario, like in India (according to the IEA), the energy mix eliminates the efficiency advantages of the electrification and creates a wash on CO_2-emission level, in a best-case scenario when the machine is used in the Northern European Region NER, the decarbonization potential is up to 90% compared to a diesel engine.

A step in between, not requiring changing the machine architecture as drastic as going to a battery-electric machine, would be the use of alternative fuels. A fuel which recently gains attention is HVO, Hydrotreated Vegetable Oil. It has the potential to reduce CO_2e emissions by up to 90% and has a high engine compatibility, but the availability in bigger masses is currently still a challenge, in addition to a higher price challenging TCO. Furthermore, LPG and CNG are also alternatives with lower CO_2e-emissions, but their advantage is compensated by the lesser efficiency of the gas engines and thus equates in a wash on emissions-level. Hydrogen/H_2 is also an emerging alternative, whereof the machine design for storage and depending on the technology used (combustion engine or fuel cell) is also subjected to a radical redesign in its architecture.

Closing the loop to the motivation of machine decarbonization, depending on the goal and the requirements a machine manufacturer wants to fulfill, several steps and their impact have been highlighted in this paper. It can be used as a guide determining what to do to achieve a certain level of decarbonization. Component swap could be sufficient for lower decarbonization goals or gearing up to electrification to make the vehicle locally emission free, where required. The in Fluid 4.0 developed toolchain [2] for the Asset Administration Shells could be a tool to track the machine's emissions during their use-phase to gain further information about real-time and real-life decarbonization effects.

Danfoss Power Solutions offers products and solutions to accompany mobile machine manufacturers on their decarbonization journey in all steps towards reaching their goals, from application knowledge, components and systems as well as software solutions for classical hydraulic as well as electric machines. Simulative and test-based decarbonization estimation is part of the support, to make future machines ready for a sustainable future and a world worth living in it.

7. References

[1] "Fluid 4.0 Research Project." Dec. 01, 2025. [Online]. Available: https://fluid40.de

[2] IDTA, *Submodel Carbon Footprint*, 02023, Mar. 2025. [Online]. Available: https://industrialdigitaltwin.org/en/wp-content/uploads/sites/2/2025/03/IDTA-02023_Submodel_CarbonFootprint.pdf

[3] Science-based Targets Initiative, Jan. 22, 2026. [Online]. Available https://science-basedtargets.org/

[4] Carbon Disclosure Project, Jan. 22, 2026. [Online]. Available www.cdp.net

[5] Schumacher, A. Hanpantsurova, O., CO_2 use phase calculation – a status update from the (Fluid 4.0) project work, Hannover Industry fair presentation, 2025

[6] Green et al., DEXTER – The Application of a Digital Displacement® Pump to a 16 tonne Excavator, FPMC/Bath, 2018

[7] Rahmfeld, R.; Ivantysynova, M.; Weber, J.: Displacement controlled wheel loader — a simple and clever solution. Dresden, 4th International Fluid-power colloquium, 2004

[8] Schneider, M., Koch, O., Weber, J., Green Wheel Loader – improving fuel economy through energy efficient drive and control concepts, Dresden, 10^{th} International Fluid-power colloquium, 2016

[9] Lagarde et al., Danfoss Digital Displacement & Editron: An efficient electro-hydraulic system for mobile applications, 13th IFK/Aachen, 2022

[10] IEA International Energy Agency, Data and statistics, 2024 dataset, available: https://www.iea.org/data-and-statistics/data-sets

Biography

Senior Director **Dr. Andreas Schumacher** is responsible for Sustainability and Product Compliance for the complete Danfoss Power Solutions segment. He joined Danfoss in 2007 as a simulation engineer after his PhD in mobile machinery tire and driving dynamics simulations at the Technical University of Braunschweig under the supervision of Professor H.-H. Harms. The career development over the nearly 20 years in Danfoss increased his responsibilities and changed from Engineering to the current role. Dr. Schumacher is also author and co-author of over 30 journal and conference papers as well as presentations. As part of his current role, he is representing Danfoss Power Solutions externally in the field of mainly Sustainability in regulatory, scientific/research and business contexts and further publications like publicly available podcasts (e.g. on Spotify).