

Modeling and Simulation of a Direct Heat Recovery System for Cabin Heating in Battery-Powered Mobile Machines

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Abstract

The transition from internal combustion engines (ICE) to alternative technologies—such as battery-electric powertrains—in mobile machinery places increased demands on thermal management systems. Cooling requirements below the ambient temperature during the summer, and intensive heating requirements during the winter, lead to holistic but complex integrated solutions where energy efficiency is of high priority. Research into integrated system solutions including heat pumps and waste-heat recovery has been carried out mainly on passenger cars. In this study, mobile machines are considered, and an articulated excavator-loader—also known as backhoe loader—is used as an example. Apart from operating tasks, times, and conditions, the system architecture under the hood differs from architectures usually found in passenger cars, including working hydraulic systems. During the early stages of vehicle development, modeling and simulation of integrated thermal management systems are crucial for proof-of-concept, developing control strategies, and understanding subsystem interactions. These processes rely on data that would otherwise require testing on a complete vehicle. This paper presents a model of a heat recovery system for cabin heating using the DLR ThermoFluid Stream Modelica library, together with input data from previous research based on experiments on a series-hybrid electric machine. The study investigates the initial feasibility and performance of a direct heat recovery system for the architecture of a battery-powered mobile machine. The results show that a simple system design can provide a strong foundation for cabin heating under many of the studied excavating conditions, though it does not fully match the performance of the reference system, which is supplied with heat from an ICE. *Keywords: Thermal management, electric vehicle, heat recovery, cabin heating, mobile machine, ITMS*

1 Introduction

Battery-powered vehicles have become a common sight on the roads. Despite this, the electrification of heavy off-road mobile machines seems delayed in comparison with passenger vehicles. This can be partly explained by

small production series and the design challenges arising with varying or unknown duty cycles, in combination with high performance requirements, and end user expectations (Beltrami et al. 2021; Lajunen et al. 2016). Mobile machines are specialized production vehicles designed for specific tasks, where reduced operating costs, minimized downtime, and enhanced performance drive the electrification (Monnay 2017; Lajunen et al. 2016). Battery as an energy storage technology is a main contender in this ongoing transition (Niemelä et al. 2023), where energy density, component costs and demanding operating conditions are some of the major challenges. To mitigate costs for end users and enhance the viability of battery-powered mobile machines, energy efficiency is a high priority—particularly because the cabin requires substantial energy for heating during winter—where thermal management systems play an important role.

Replacing the internal combustion engine (ICE) with electric motors will likely increase the total energy efficiency of the vehicle. However, removing the ICE will also remove a lot of available waste heat, which was previously especially useful during winter to keep the cabin warm and comfortable. Instead, this energy needs to be taken from somewhere else. Ideally, the waste heat previously recovered from the ICE could instead be recovered from the electric motors in a battery-powered mobile machine. On the other hand, the amount of available heat flow from one single source may not always be sufficient to cover the cabin heat demand. Heat sources on these types of vehicles are also specifically dependent on the operating mode of the machine (Lagerstedt et al. 2024). An integrated thermal management system (ITMS)—that enables the collective recovery of heat from multiple components and subsystems within the machine—is therefore a necessary strategy moving forward in order to reduce the energy consumption of the thermal management system and to fulfill the runtime requirements of the machine at lowest possible cost impact on the end user.

Unlike passenger cars, mobile machines are primarily built to perform paid work. In some cases by being stressed to the system limits during a full mission, in others by only occasional peak loads. In both cases, system cost and reliability are key aspects to ensure the profitability

ity of the operation. Since the maximum available runtime at high-power utilization is crucial for a mobile machine, the overall vehicle efficiency at these operating points defines the minimum required energy storage needed to reach the lower acceptable runtime—and thus the machine cost. As illustrated in Figure 1, the potential for recovering waste heat is greatest during short runtimes—corresponding to high-utility operation—where effective heat recovery methods are most beneficial, while longer runtimes may require supplementary heating, though this does not necessarily affect the required energy storage if the added energy remains small compared to the high-utility consumption.

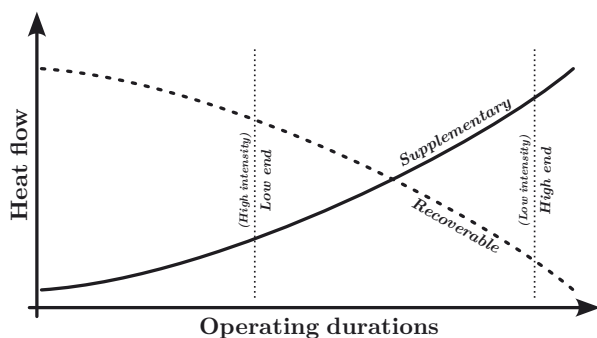


Figure 1. Conceptual representation of the heat flows over operating durations—from a full energy storage to empty—for an electrified mobile machine during cold conditions. At short operating durations—corresponding to high-power utilization—the amount of recoverable heat is high, reducing the need for supplementary energy. As power utilization decreases and operating durations increase, recoverable heat drops, and supplementary heating becomes increasingly necessary. Fictive duration limits, marked as 'Low end' and 'High end' along the horizontal axis, illustrate the design requirement for a supplementary heat source.

Relying solely on waste-heat sources from a battery-electric powertrain may not provide satisfactory heating results in the cabin if the power output from the vehicle is not high enough. To counter this issue, a simple and commonly used method in the history of electrification has been to add resistive heating elements to supplement insufficient heat flow (He et al. 2024). Another solution is to use the existing air conditioning system as a heat pump, which is gaining attention due to the range loss often related to the use of resistive heaters (Kwon et al. 2024). Even if a heat pump system can be designed so that waste heat is recovered from various heat sources in the vehicle, a heat pump is a supplementary heat source requiring energy to power the compressor. Thus, an efficiency limit is introduced which is defined by the energy consumption of the heat pump system. This limit can be passed with a direct heat recovery system, if the amount of waste heat within the system is high enough for the heating demands.

Since the most studied use case within the research of ITMS solutions still is the passenger car (Leoncini et al. 2024), more knowledge is needed regarding mobile ma-

chines and the implications of differences in system architecture and duty cycles on the availability of waste heat—and viable methods for recovering it.

1.1 Mobile Machines

In this and previous studies, an articulated excavator-loader—also known as backhoe loader—is used to represent a mobile machine (Lagerstedt et al. 2024; Lagerstedt et al. 2025). The Huddig 1370T, illustrated in Figure 2, is an example of an electric hybrid mobile machine with a specified standard weight of 14.6 t and a top speed of 50 km/h.



Figure 2. Illustration of an articulated excavator-loader, the Huddig 1370T—an example of a mobile machine capable of both road transportation and load handling, featuring a front loader and a rear excavating unit.

Mobile machines in general—and Huddig machines in particular—are multi-purpose vehicles. The main purpose is rarely human transportation—however, many mobile machines still have a physical operator on board with requirements on comfort and visibility. Standardizing mobile machine duty cycles is challenging, due to the variety of functions, capacity and operating conditions. In a previous study, one approach to evaluate thermal loads during extreme, high-utility operation was presented (Lagerstedt et al. 2024). The approach was based on dividing the machine's mode of operation into the two known, most energy-intensive and contrasting modes—transportation and excavating. Combining the operating modes with ambient temperatures, forms a coordinate system of machine operation illustrated in Figure 3. Extreme operating points were selected in each corner and evaluated experimentally on the electric hybrid machine Huddig 1370T to estimate the thermal loads. The thermal loads divided into approximate temperature categories, together with the cabin heating demand, is illustrated in Figure 4.

In this study, a proposed system to recover parts of the available waste heat in order to warm the vehicle cabin is modeled, simulated and evaluated. The proposed system is a direct heat recovery system, meaning that waste heat is transferred to its destination as sensible heat, without phase changes or significant mechanical work on the transport medium. The system covers heat

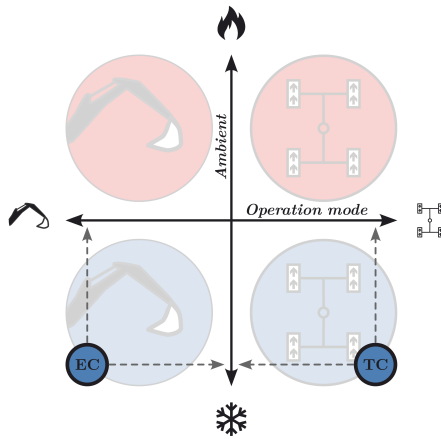


Figure 3. Overview of the operating scenarios for a mobile machine, defined by ambient temperature on the vertical axis and operating mode on the horizontal axis. 'Excavating Cold' (EC) and 'Transportation Cold' (TC) marks operating points previously evaluated by experiments—representing corner cases during cold ambient conditions (Lagerstedt et al. 2024). The dashed lines illustrate the operating point directions of interest to evaluate through simulations in this paper.

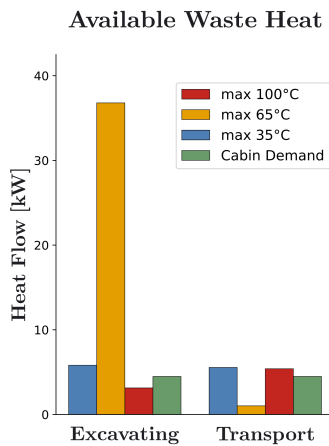


Figure 4. Bar chart from previous work, illustrating available waste-heat flow on a battery-powered mobile machine at worst case operating points during cold ambient conditions—excavating and transportation at -15°C (Lagerstedt et al. 2024).

recovery in the two separate operating modes excavating and transportation. During excavating, heat is recovered from the hydraulic system—which is significant for a mobile machine—along with the electric motors and inverters powering the hydraulic pumps. The heat recovery principle for excavating is illustrated in Figure 5a. For transportation, the heat recovery principle is more similar to that of a road transportation vehicle and is illustrated in Figure 5b.

1.2 Contributions

This study investigates the initial feasibility and performance of an ITMS for the architecture of a battery-powered mobile machine. A simple and low-complexity

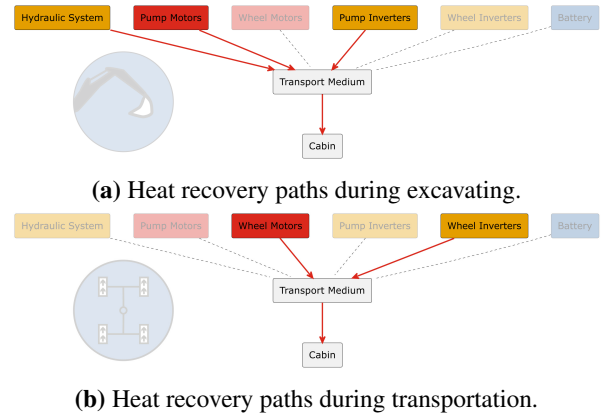


Figure 5. Principal overview of the proposed direct heat recovery system during excavating and transportation respectively, as studied in this paper. Heat is recovered from the active subsystems via a transport medium that delivers thermal energy to the cabin. Solid red arrows indicate the active heat flow paths in the respective operating mode, while dashed lines represent inactive heat paths in the ITMS. The heat sources are colored according to the temperature categories used in Figure 4.

system design of a heat recovery system is suggested, adopting the main principle of a traditional heat recovery system—but replacing the ICE with heat sources related to an electrified mobile machine. By the modeling and simulation of the proposed heat recovery system, a wide variety of operating points can efficiently be evaluated, and the effect of control strategies can be understood.

2 Modeling

The models presented in this section were made using the DLR Thermofluid Stream Library (TFS) (Zimmer 2020; Zimmer, Meißner, and Weber 2022), together with the Modelica Standard Library and the modeling and simulation tool OpenModelica v1.22.2. Both the libraries used and the simulation tool are open-source, which was an important reason behind the selected approach. Additionally, ITMSs in electric vehicles can evolve into complex designs with many actively controlled flow routes, where the TFS library can serve as a strong alternative (Zimmer, Meißner, and Weber 2022). Two models were created, where the first model represents a traditional heat recovery system on a vehicle powered by an ICE, in this study acting as a reference system. The second model represents the proposed system, but with two different control strategies. The control strategies refer to the mass flow control of the transport medium—the first maintains the same fixed flow as the reference system, while the second actively controls the flow to keep the electric motors at their maximum temperature.

To evaluate the system models in the different operating points illustrated in Figure 3, two parameters are used—ambient temperature T_{amb} for the vertical axis, and intensity factor X_I for the horizontal axis. The intensity factor

is a simplified representation of both operating mode and degree of operating intensity, where negative and positive values correspond to excavating and transportation respectively, with -1 and 1 both being equal to maximum intensity. The models are evaluated in the temperature range -15 to 15°C .

2.1 Reference System

First, a baseline system was modeled representing a heat recovery system of a traditional vehicle powered by an ICE, and is illustrated in Figure 6. The model consists of two separate circuits—one transport medium circuit delivering heated glycol-mixed water to the heating core in the cabin, and one circuit heating ambient air and delivering it to the cabin.

The transport medium circuit, highlighted with thick blue lines, is modeled as an open circuit with a fixed temperature source of 82°C and a constant flow. The constant flow is modeled with a pump component with input signal from a mass flow regulator, consisting of a PI controller and a limiter. Due to the excessive heat flow available in the ICE, and the thermostat maintaining the engine temperature via an external heat rejection system, the heat supply to the cabin is assumed to be constant. The temperature value was measured in previous work (Lagerstedt et al. 2024).

The second circuit, highlighted with a purple zone, corresponds to the cabin and the fresh air supply, modeled as an open circuit with a fixed air flow—maintained with the same method as the transport medium—corresponding to the maximum possible air flow based on previous measurements (Lagerstedt et al. 2024). The cabin is modeled as a volume component, with the output temperature state representing the cabin temperature in this study. The temperature of the source component is defined with the parameter T_{amb} .

2.2 Proposed System

The system model—covering the hydraulic system, pump motors, pump inverters, wheel motors and wheel inverters—is illustrated in Figure 7, and operates according to the two heat recovery principles presented in Figure 5a and Figure 5b. The system consists of four circuits—two representing the working hydraulic system and its heat rejection system, one transport medium circuit, and a cabin air flow circuit identical to that found in the reference system. Aside from TFS library components described in detail in (Zimmer, Meißner, and Weber 2022), standard Modelica components are used for the control logic and to group the inverter and electric motor models for space-saving purposes. The heat losses rejected by each part of the system are specified in the constants, multiplied with the absolute value of the intensity factor $|X_I|$.

The working hydraulic system, highlighted in a yellow zone in Figure 7, was based on a model used in previous work but with slight modifications (Lagerstedt et al.

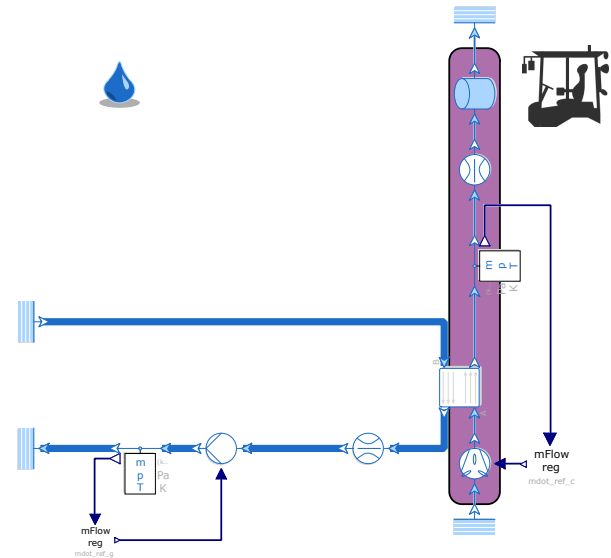


Figure 6. Modelica model of the reference system—aimed to represent a traditional vehicle powered by an ICE—composed of a cabin highlighted in purple and a transport medium circuit modeled as a source with constant flow and temperature.

2025). In this study, a PI controller is used to control the ambient chiller, while constant heat flow and mass flow are used to create a more computationally lightweight model. The hydraulic circuit is modeled as a closed system consisting of a reservoir, a flow restriction, and two heat exchangers—one for heat recovery and one for heat rejection. The circuit leading through the heat rejection exchanger is designed to maintain a maximum allowed temperature of 65°C in the hydraulic reservoir, since the hydraulic heat flow far exceeds the cabin demand. The model represents the return line of the working hydraulic system, transporting the hydraulic heat losses to the ambient chiller. The hydraulic heat losses are modeled as a conduction element and a pump component. The pump component is controlled to maintain a specified hydraulic flow. The conduction element is supplied with a specified heat flow. Both the specified mass flow and heat flow are multiplied with the absolute value of the intensity factor $|X_I|$.

The thick blue lines in Figure 7 highlights the transport medium circuit, creating the integration between vehicle heat sources and the cabin. For each operating mode, the active heat sources are connected in series, while the circuits for the inactive systems are bypassed. The activation and deactivation of systems are controlled by Modelica Standard Library components, together with switching valves from the TFS library. The pump component in the transport medium circuit is controlled by a mass flow regulator—described earlier in the paper—which maintains a fixed flow rate identical to that of the reference system. An alternative control method for the transport medium mass flow rate was also suggested which maintains the active motor temperatures at 100°C —an approximate maximum operating temperature—and is illustrated

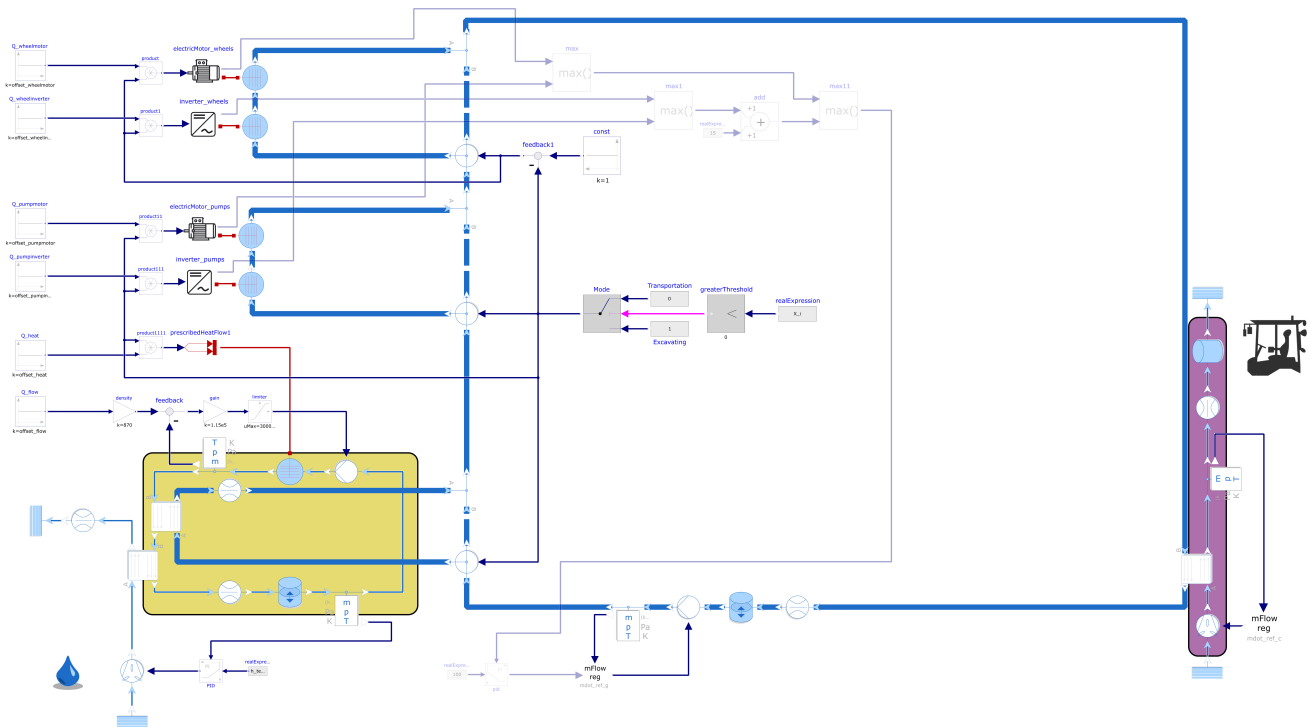


Figure 7. Modelica model of the proposed system, composed of a cabin highlighted in purple, heat sources, and a transport medium circuit highlighted with thick blue lines. The heat sources in the left area of the figure are modeled in series, with loops enabled by switching valves depending on the active operating mode parameter X_I . The hydraulic system, highlighted by the yellow zone, is enabled together with the loop for the inverter and electric motor powering the hydraulic pumps. The transparent lines and components correspond to the alternative mass flow control strategy.

by the transparent components and lines in Figure 7.

To obtain a system model slightly more compact and easier to read, separate but identical models to represent electric motors, and inverters were created, as illustrated in Figure 8. The model converts a real signal into a heat flow, acts as a thermal mass, and converts the temperature state of the heat port into an output value in Celsius. The model is built using Modelica Standard Library components, and the only difference between the motor and inverter models is the icon.

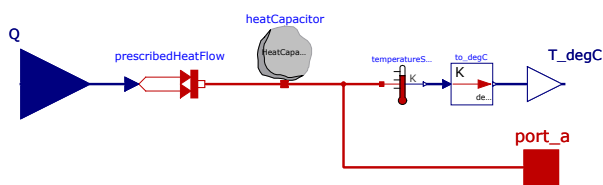


Figure 8. Modelica model of the inverter and electric motor—used to improve the readability of the system model—composed of a prescribed heat flow, a heat capacitor, and a temperature conversion component. The only differences between the inverter and motor models are the icon and the heat capacity parameter value.

3 Results

In this section, simulation results from the reference system and the proposed direct heat recovery system for

a battery-powered mobile machine are presented. The reference system represents a conventional cabin heating system based on heat recovery from an ICE. The proposed system adopts the main principle of the reference system—but with heat recovery from alternative sources—and is evaluated using two different strategies. First, with the transport medium mass flow rate fixed at the same level as in the reference system—and second, with the mass flow rate controlled to maximize the electric motor temperature. The two strategies are evaluated in comparison with the reference system and with one another. Contour plots are used to illustrate performance across different operating modes, ambient temperatures, and operating intensities.

In Figure 9, the simulated cabin temperature from the reference system is shown, using the maximum available heating power. The straight contour lines illustrate how the traditional cabin heating performance is independent of operating mode and intensity. The different cabin temperatures are an effect of the intake air temperature varying with the ambient temperature on the y-axis. The high absolute temperature values observed are a consequence of the system's passive exposure to ambient temperatures not being included in the model. This result is used as a baseline for comparison with the proposed system.

Figure 10 shows the simulated cabin temperature from the proposed heat recovery system with a fixed transport

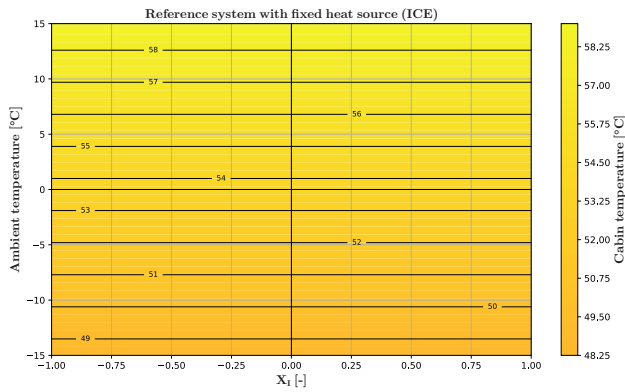


Figure 9. Resulting contour plot of the simulated cabin temperature using the reference system at maximum heating power, with fixed transport medium mass flow rate and temperature. Ambient temperature is represented on the y-axis and intensity factor on the x-axis, where negative and positive values correspond to excavating and transportation, respectively.

medium mass flow rate—relative to the reference system results shown in Figure 9. The mass flow rate is the same as that of the reference system. Negative values of cabin temperature difference means that the cabin temperature is lower compared to the reference system, which is true for all simulated operating points. The cabin temperature is generally higher in excavating mode—denoted by negative values of X_I in the plot—compared to transportation mode, denoted by positive values, as indicated by the smaller cabin temperature differences.

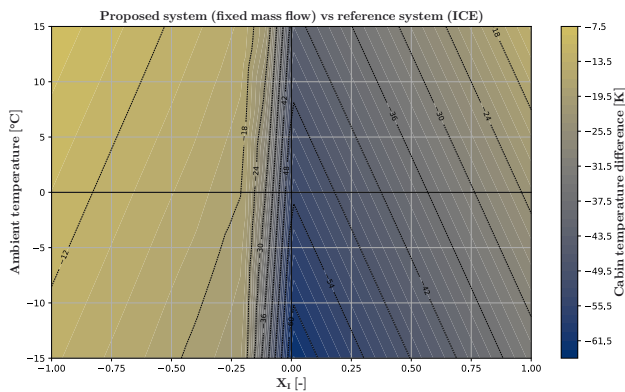


Figure 10. Resulting contour plot of the simulated cabin temperature using the proposed system at maximum heating power—with fixed transport medium mass flow rate—shown relative to the reference system results. Ambient temperature is represented on the y-axis and intensity factor on the x-axis, where negative and positive values correspond to excavating and transportation, respectively.

Simulation results for the proposed system, but with active control of the transport medium mass flow rate is seen in Figure 11. Compared to the results with a fixed mass flow rate, the cabin temperature is more similar between the operating modes—excavating and transportation. The cabin reaches slightly higher temperatures during medium

to high intensity transportation, while the opposite is true across all intensities of excavating.

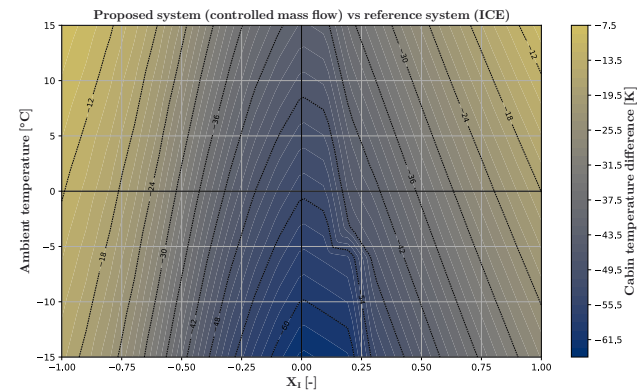


Figure 11. Resulting contour plot of the simulated cabin temperature using the proposed system at maximum heating power—with controlled transport medium mass flow rate—shown relative to the reference system results. Ambient temperature is represented on the y-axis and intensity factor on the x-axis, where negative and positive values correspond to excavating and transportation, respectively.

To better understand the results in Figure 11, a comparison between the two strategies is shown in Figure 12, where the cabin temperature achieved with controlled transport medium mass flow rate is shown relative to the fixed flow rate case. It is observed that the cabin temperature during transportation increases with the control strategy, but decreases during excavating. One exception to the improved performance during transportation is observed at intensities $0 \leq X_I \leq 0.2$, where the electric motors do not reach their maximum temperature and therefore do not demand an increased mass flow rate. During excavating, the strategy of controlling the mass flow rate solely to maintain the electric motors at 100°C results in reduced heat recovery from the working hydraulic system. Even though a significant amount of waste heat is available in the hydraulic system at most operating points, the recovered heat depends on—and is limited by—the transport medium mass flow rate, as the hydraulic system temperature is maintained at 65°C by the ambient chiller.

In Figure 13, the recovered heat flow from each subsystem and the cabin's heating performance are shown for the worst-case operating points during excavating and transportation—indicated by 'EC' and 'TC' in Figure 3. Apart from confirming the earlier presented results—that the heating performance of the cabin with the proposed heat recovery system is lower than for the reference system—it is shown that all the available waste heat from the motors and inverters are recovered in both operating modes. However, during excavating only a fraction of the available hydraulic waste heat is recovered. As already mentioned, this is due to the temperature limit in the hydraulic system, here set to 65°C to protect the oil from degrading.

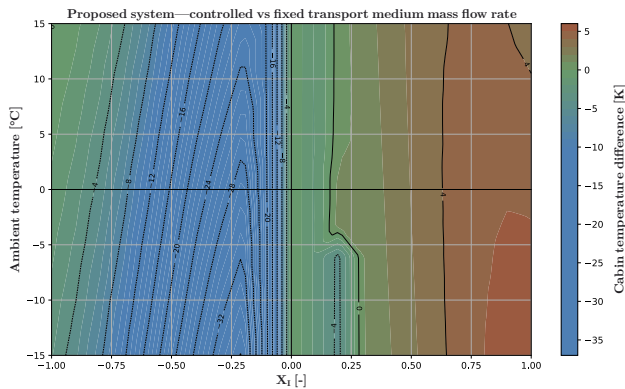
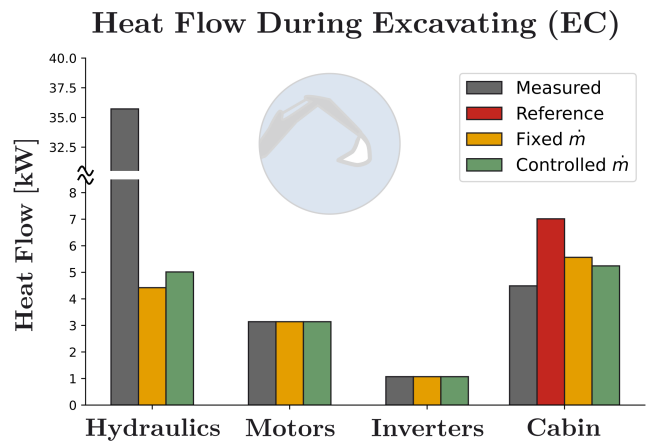


Figure 12. Resulting contour plot of the simulated cabin temperature using the proposed system at maximum heating power—with controlled transport medium mass flow rate—shown relative to the proposed system results with fixed mass flow rate. Ambient temperature is represented on the y-axis, and intensity factor on the x-axis, where negative and positive values correspond to excavating and transportation, respectively.

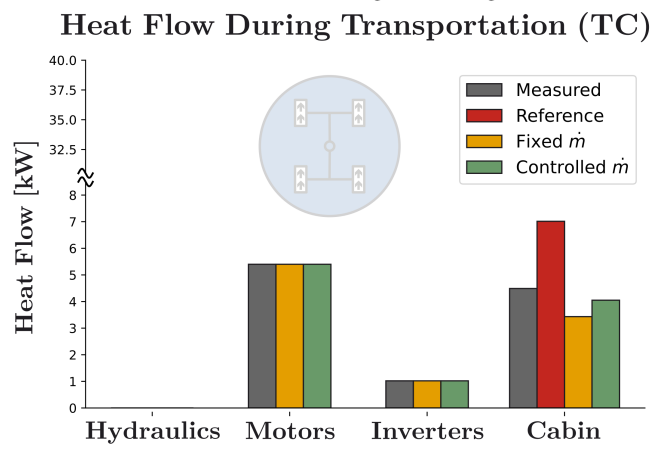
4 Discussion

The purpose of this paper was to investigate and understand the potential of direct heat recovery for warming the cabin of a battery-powered mobile machine—and to what extent the heat source of an ICE can be replaced by multiple alternative sources. A proposed direct heat recovery system was modeled and simulated using two different control strategies, and the results were compared with a reference system. The focus of this study was to understand the initial feasibility of the direct heat recovery system principle. Even though previously measured data has been used within the model, some uncertainty remains regarding component parameters. Therefore, the results are compared between models with equal uncertainty, and absolute values should be interpreted with caution.

The results suggest that the heat recovery system and control strategies as presented in this paper do not match the performance of the reference system—despite the available waste heat shown in Figure 4, where the heat exceeds the cabin demand. However, it is demonstrated that a simple system design can warm the cabin while keeping the included system components within their temperature limits. The results further indicate that the heating performance can be improved by the selection of control strategy—especially in order to maximize the heat recovery from the working hydraulic system during excavating. Even though the performance in the reference system is not reached, there is room for further improvement, including solutions to close the performance gap. To improve the heat recovery during excavating, the transport medium flow could be divided into two parallel circuits, with the power electronics in one circuit, and the hydraulic system in the other. This way, maintaining the electric motor at 100°C will not negatively affect the heat recovery from the working hydraulic system. Including the bat-



(a) Heat flows during excavating.



(b) Heat flows during transportation.

Figure 13. Simulated heat flows in the worst case operating points, marked as 'EC' and 'TC' in Figure 3. The categories on the horizontal axis refer to the subsystems in the studied heat recovery systems. The gray bars correspond to the measured values of available waste heat and cabin heat demand, illustrated in Figure 4. The red bar is the cabin heating performance in the reference system. The yellow and green bars show recovered heat from working hydraulics, motors and inverters, and the cabin heating performance for each control strategy respectively.

tery in the heat recovery system is also a possible option, but it would likely increase system complexity due to its low nominal temperature. To close the heating performance gap, stored electric energy in the battery could be used when needed—either through the implementation of a heat pump or via resistive heating.

A direct heat recovery system is—as indicated by the results—dependent on the actual temperature on the individual heat sources. In this study the results are presented during steady state, after 8 hours continuous operation. In a product application, the heat-up time before heat can be effectively recovered becomes important, and should be considered in a comparison with alternative systems designs or principles.

The presented models are simplified such that the ambient effects on the system are not considered, other than the

simulation starting temperature, and the intake air temperature of the cabin heating core. This makes the resulting cabin temperatures only valid in relation to the reference system, where the same simplifications are used. Additionally, a cabin on a vehicle commonly uses an air recirculation system, not included in the models presented here. The absence of air recirculation leads to an overestimation of the modeled heating power, which can be observed in Figure 13, and an underestimation of the cabin temperatures—however, the same applies to both systems, keeping them comparable.

Finally, using the cabin performance powered by an ICE as a reference system and a baseline to determine whether a proposed system design is 'good enough' may not be entirely relevant—due to the fact that cabins on traditional vehicles are not designed for limited heat sources and high energy efficiency. However, it can serve as a useful benchmark for evaluating the specific performance of a chosen design and control strategy—particularly in future assessments aimed at closing the heating power gap.

5 Conclusions

Direct heat recovery from inverters, electric motors, and the working hydraulic system is not sufficient on its own to replace the heat delivered by an ICE—but it can provide a significant foundation for cabin comfort management during excavating, offering low system complexity.

Acknowledgments

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