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Eco-operated, Modular, highly efficient, and flexible multi-POWERtrain for long-haul heavy-duty vehicles

Acronym: **EMPOWER**

Grant Agreement No.: **101096028**

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Publishable Executive Summary

This deliverable describes the work performed in EMPOWER in WP4 Modular and flexible vehicle architecture and there especially the advancements and results of Task 4.4 Innovative and efficient heating, ventilation, and air conditioning. In the document the progress and achievements in determination of the needed heating and cooling power, the implementation of the improved cabin insulation, and the design of the HVAC system are reported.

The state-of-the-art cabin was delivered from IVECO to AIT and was first equipped with a heating and cooling system powered by a controllable process thermostat and an improved heating and cooling system with an additional heat exchanger for reusing waste heat of the cabin. Furthermore, the cabin was equipped with a measurement system for the determination of the heating and cooling power. Measurements were performed in the climatic chamber at AIT under different ambient conditions. After this baseline measurement the cabin insulation was improved, and measurements were repeated. With this, an estimation of the needed heating and cooling power could be conducted for different HVAC system configurations.

In parallel a concept and design for an HVAC system based on the refrigerant CO_2 (R744) was created. The system is capable of working in heat pump mode, which should further enhance the energy consumption for conditioning the cabin. For the heating mode also Infrared heating panels are installed in the cabin which reduced the needed air temperature in the cabin, which in turn also further decreases the needed energy consumption of the HVAC system.

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Abbreviations and Nomenclature

Table 1: List of Abbreviations and Nomenclature

Symbol or Shortname	Description
CAD	Computer Aided Design
CAN	Controller Area Network
EV	Expansion Valve
GWP	Global Warming Potential
HV	High Voltage
HVAC	Heating-, Ventilation-, and Air Conditioning System
IR	Infrared
LIN	Local Interconnect Network
MAC	Mobile Air Condition
MEB	Modular electric-drive toolkit (German: Modularer E-Antriebs Baukasten)
ODP	Ozone Depletion Potential
ppm	Part per million (10^{-6})
PTC	Positive Temperature Coefficient
SV	Safety Valve
ZE-HDV	Zero-Emission Heavy-Duty Vehicles

1 Introduction

The **objective of EMPOWER** is to deliver two modular and flexible Zero-Emission Heavy-Duty Vehicles (ZE HDVs) of Vehicle Energy Consumption Calculation Tool (VECTO) group 9 with a Gross Vehicle Weight (GVW) of at least 40 tons, both at Technology Readiness Level (TRL) 8. One of the trucks will be a Fuel Cell Electric Vehicle (FCEV) suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km. The second one, being a Battery Electric Vehicle (BEV), will be designed for regional distribution mission profiles with a maximum unrecharged driving range of 400 km.

The **ambition of EMPOWER** involves the development, implementation, and demonstration of these vehicles at TRL 8, guaranteeing a maximum load capacity of not less than 90 % compared to conventional trucks of the same vehicle class and making them ready to enter the market in 2029 with equal Total Cost of Operation (TCO) as 2020 engine-based solutions, assuming a production volume of more than 10,000 vehicles/year.

To reach the objectives and ambition, EMPOWER will draw from a rich portfolio of technology bricks in the following **AREAs**:

AREA I **Component Design and Modularity** dealing with the design and implementation of (1) a modular vehicle system architecture, (2) a modular high voltage architecture, (3) a modular low voltage E/E architecture, (4) a FC system with high reliability and extended operational lifetime with a modular energy storage, (5) a highly efficient e-axle, (6) an optimised thermal- and energy management, (7) an optimised HVAC system featuring CO_2 as refrigerant and infrared heating panels, (8) an electrified distributed braking system, and (9) digital twin models of the demonstrator vehicles. The modular and flexible vehicle architecture allows the developments in EMPOWER to be carried over to other vehicle platforms.

AREA II **Integration and Infrastructure** dealing with (10) an innovative Human Vehicle Interface for optimised control of the vehicle systems, featuring Vehicle-to-Grid communication and eco-routing, (11) a fleet management system for the integration of ZE HDV into the fleet, (12) an overall LCA and TCO assessment, and (13) the operation of a green hydrogen infrastructure for ZE HDV needed for the long-haul European cross-border demonstration.

The integration of all developed components from AREA I and AREA II into the demonstrators will prepare them for the demonstration phase. The developments in these two AREAs pave the way for a successful demonstration of the vehicles in AREA III.

AREA III **Demonstration** will be performed in two stages. **Stage 1** demonstrates the maximum unrefuelled/unrecharged range at the Balocco Proving Ground (IT), whereby the BEV will be tested in a version with only one battery pack. Configurations mit higher numbers of packs will then be simulatively extrapolated. **Stage 2** is the concluding six-month demonstration in different real-world use cases (UCs). Additionally, to guarantee high utilisation of the demonstrators, IVECO will use both vehicles for the transportation of goods between its manufacturing sites and logistic hubs.

This deliverable deals with technology brick (7), an optimised HVAC system featuring CO_2 (R744) as refrigerant, infrared heating panels for comfortable and energy efficient heating, and an improved thermal insulation of the driver cabin. In this document the work done so far is summarised and an overview of the planned HVAC concept is given. Further system implementations and measurements will be reported in Deliverable D4.4. later in the project.

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2 Cabin insulation and HVAC system

Conventionally, the HVAC systems of vehicle cabins rely on excess heat produced by the internal combustion engine to heat up the air inside. This excess is available in greater quantities than necessary; therefore, the thermal insulation of the cabin was not a priority before. Besides the thermal conductivity of the cabin's surfaces, another aspect which can be improved is how the already conditioned air inside the cabin is used. In conventional cases, the air escapes through an opening on the back of the cabin or through other unwanted leaks.

In this chapter, effects of an improved thermal insulation will be demonstrated. Additionally, using an air-air heat exchanger, the conditioned air of the cabin will be used to treat the incoming fresh air to further reduce heating and cooling power consumption.

2.1 Insulation

Insulating mats have been applied to the cabin with the intention to reduce the thermal conductivity of the walls. The insulation material has a thermal conductivity of 0.036 W/(m.K) and a thickness of 25 mm. A reduced thickness of 13 mm is used on the top to lower the weight which needs to be supported by the headliner.

In theory, the gap between the interior trim panels and the sheet metal parts is sufficient to fit additional insulation. However, the experiments required removing the insulation in a short time between measurements, therefore they have been applied on the surface of the inside panels.

Figure 1: Insulation of overhead area.

Figure 2: Insulation of compartments.

Since the water-air heat exchangers (heater core and evaporator) are located under the dashboard inside the cabin, the insulation on the front side has not been placed in the interior, but on the outside. Additionally, a

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piece of the dashboard above the heater core was removed to reduce thermal insulation between the heating/cooling medium and the cabin's air.

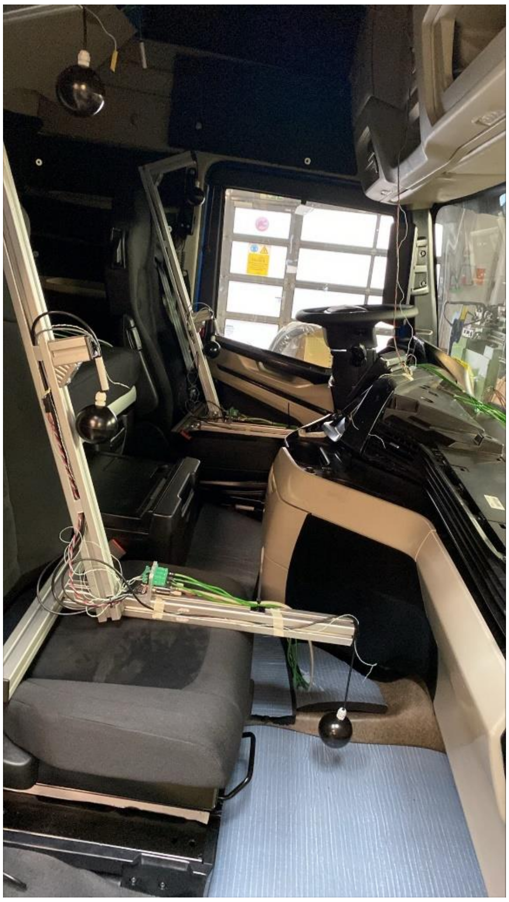

Figure 3: Floor insulation and removed dashboard piece (right side of the cabin).

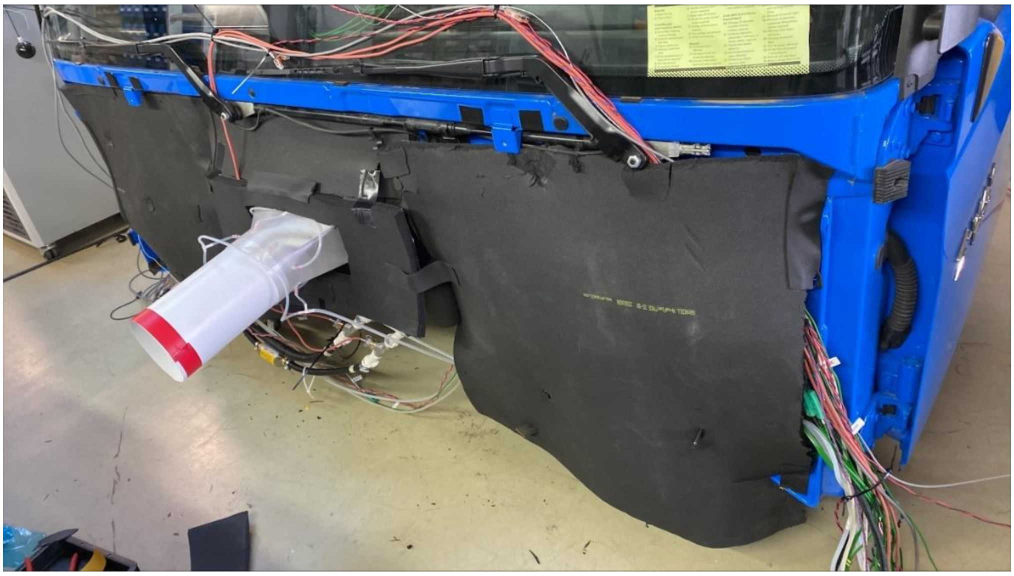

Figure 4: Insulation on the front of the cabin.

Additionally, leaks where air can escape have been located and sealed. The main opening where most of the treated air escapes is located on the back of the cabin.

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Figure 5: Insulating and sealing main cabin opening.

The leak proofing included sealing some, but not all water drainage holes on the doors, closing small openings between metal sheet parts pressed and welded together, and taping the edges of side compartment doors.

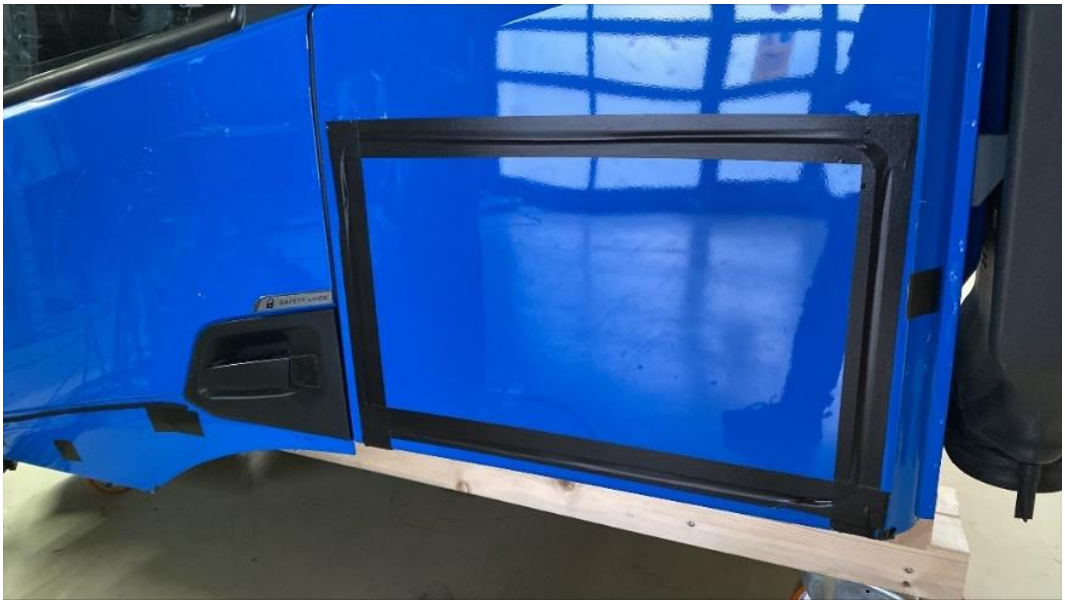

Figure 6: Sealed side compartment doors, to simulate improved rubber sealings.

The effect of the insulation can be seen on thermal images taken in the climate chamber during the HVAC consumption measurements and identification.

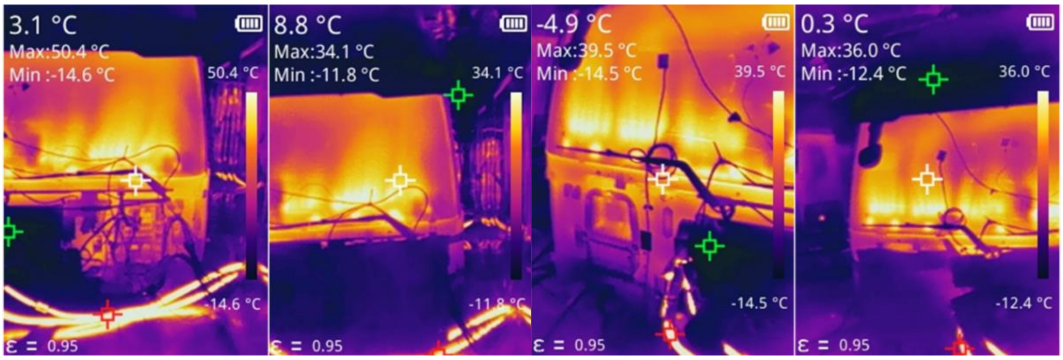

Figure 7: Effect of insulation on the cabin's front side. Left: uninsulated driver side; Middle Left: insulated driver side; Middle Right: uninsulated passenger side; Right: insulated passenger side.

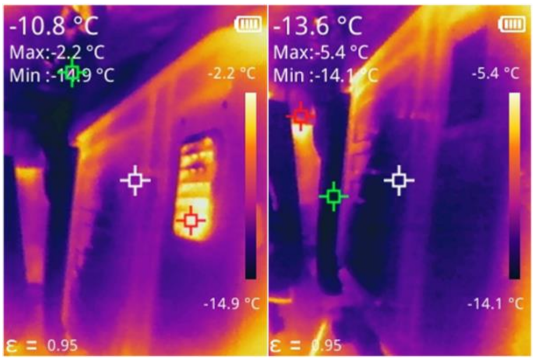

Figure 8: Effect of insulation on cabin's back side. Left: uninsulated; Right: insulated.

2.2 HVAC system with heat exchangers

Originally, the truck cabin has two operating modes: fresh air and recirculation. While taking in fresh air from the outside, an equal amount of already treated air is pushed out from the cabin at the same time. With two passengers and recirculation mode enabled, the air quality inside quickly deteriorates, and CO_2 concentration can reach 1000 ppm after just 5 minutes.

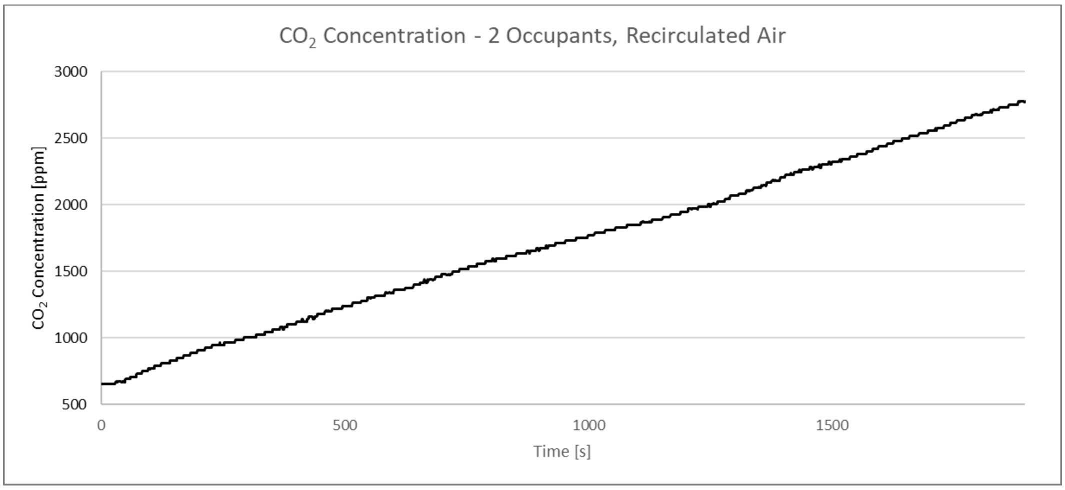

Figure 9: Cabin CO_2 concentration on recirculation.

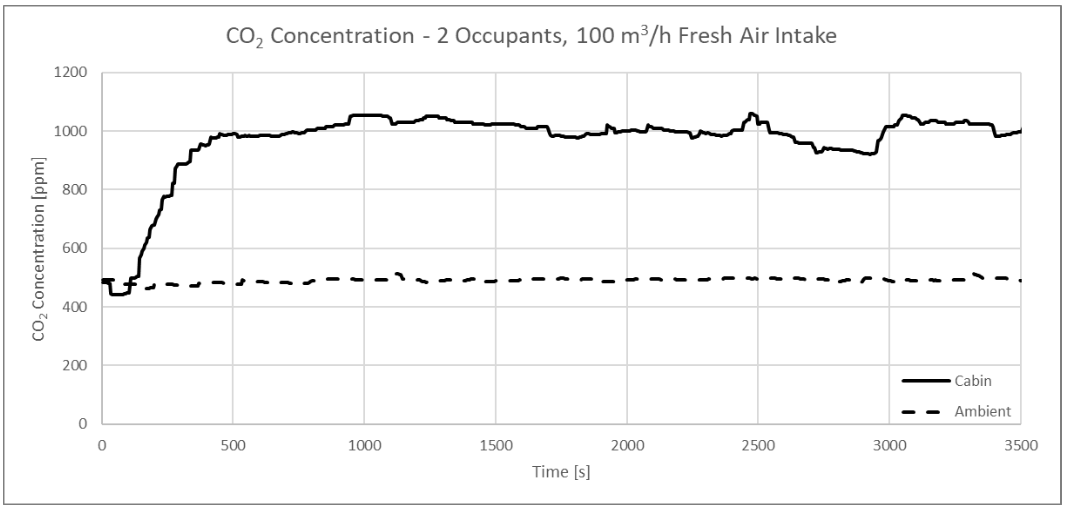

Figure 10: CO_2 concentration of the cabin with 2 occupants and 100 m^3/h fresh air inlet.

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With an additional air-air heat exchanger, it is possible to bring in fresh air while not wasting the treated air's energy by letting it escape through an opening. The next figure represents the way the heat exchanger was implemented.

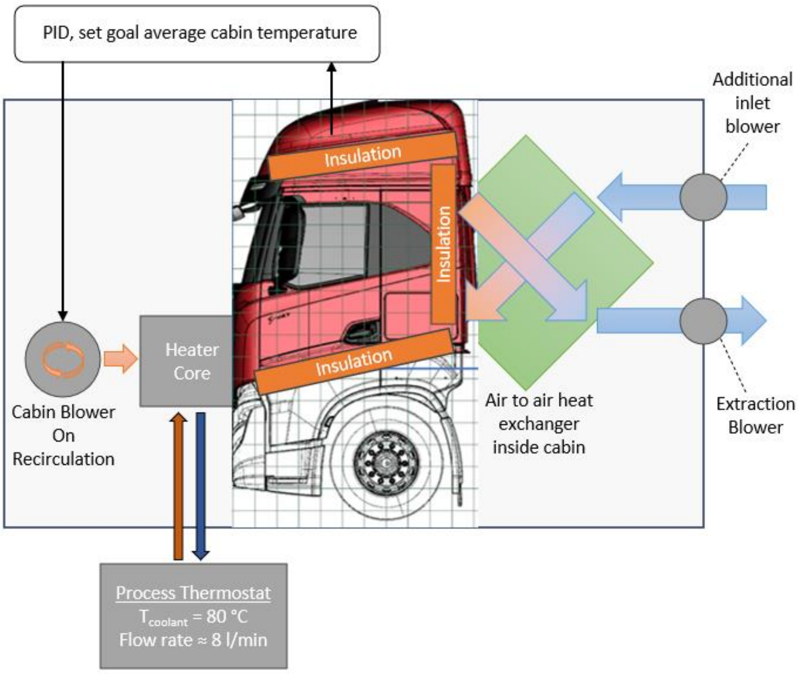

Figure 11: Schematic of air-air heat exchanger setup.

In this case, the cabin's original HVAC system is set to recirculation mode and the main blower is controlled to achieve and control a target cabin temperature. Fresh air is brought in through the heat exchanger with an additional fan. The inlet air volume flow is set to 100 m^3/h. In the other channel of the heat exchanger, air is being removed with another extraction fan. The outlet air flow is set to achieve 0 Pa cabin pressure relative to ambient. A positive overpressure would cause treated air to escape through holes, and a negative cabin pressure would bring in untreated ambient air through the same cabin leaks.

The air-air heat exchanger was placed in a side compartment. Inlet and outlet openings were cut in the compartment's door. The fresh air enters the cabin under the bed behind the occupants and the cabin's air is being extracted from the driver side.

Figure 12: Heat exchanger setup, inlet, and outlet openings.

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Figure 13: Heat exchanger setup, inlet, and outlet channels.

Figure 14: Heat exchanger inside the compartment.

A RECAIR RC160 hexagonal plate heat exchanger with a size of 360x360x200 mm has been used in the experiments. The heat exchanger's cold side has been insulated and despite its size, it fits in the compartment of the cabin without further modifications.

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3 Measurements and determination of heating/cooling power

The necessary heating/cooling power for the cabin was determined in a climatic chamber in steady state conditions. The cabin's average temperature was evaluated as the average of eight temperature sensors distributed in the interior. The recorded values were averaged over the period, where the cabin temperature, and heating/cooling power had already stabilised.

The heating/cooling power is calculated by measuring the coolant's flow rate and its temperature before and after the water-air heat exchanger in the cabin. The following equation was used:

$$P_{Heating/Cooling} = |T_{CoolantIn} - T_{CoolantOut}| * \dot{V}_{Coolant} * \rho_{Coolant} * c_{pCoolant}$$

Where:

- $P_{Heating/Cooling}$ [W] is the necessary heating or cooling power,
- $T_{CoolantIn}$ [°C] is the temperature of the coolant before entering the water-air heat exchanger,
- $T_{CoolantOut}$ [°C] is the temperature of the coolant after leaving the water-air heat exchanger,
- $V_{Coolant}$ [m3/s] is the volume flow of the coolant in the coolant circuit,
- $\rho_{Coolant}$ [kg/m3] is the density of the coolant (1042 at 80 °C and 1090 at 0 °C),
- $c_{pCoolant}$ [J/kg.K] is the specific heat of the coolant (3647 at 80 °C and 3412 at 0 °C).

The power consumption of the main blower and additional air-air heat exchanger fans have also been taken into consideration and added to the heating/cooling power to determine the total consumption.

3.1 Heating power

For the heating measurements, the following ambient and cabin conditions were applied:

- -7.2 °C ambient temperature,
- 23 °C set cabin temperature,
- 70 % ambient relative humidity,
- 7.8 l/min glycol-water coolant flowrate,
- 80 °C coolant temperature at water-air heat exchanger (heater core) inlet.

The following setups were measured:

- Original cabin with fresh air intake,
- Original cabin in recirculation mode,
- Insulated cabin with fresh air intake,
- Insulated cabin in recirculation mode,
- Original cabin with additional air-air heat exchanger,
- Insulated cabin with additional air-air heat exchanger.

The results are in the following table and graph.

Table 2: Results of HVAC measurements, heating case.

Heating Measurements, $T_{ambient}$ = -7 °C, T_{cabin} = 23 °C		
Cabin setup and HVAC mode	Consumption [W]	
Original, Fresh air	3311	100 %
Original, Recirculation	2470	75 %
Insulated, Fresh air	2886	87 %
Insulated Recirculation	2263	68 %
Original, Heat Exchanger	2776	84 %
Insulated Heat Exchanger	2571	78 %

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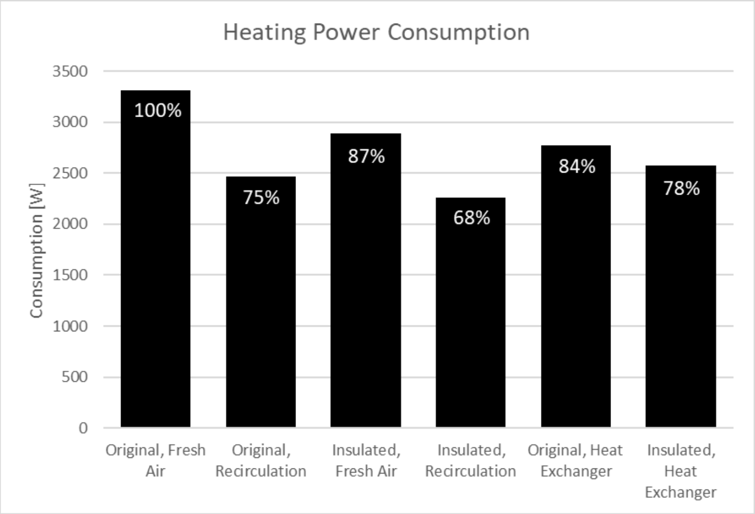

Figure 15: Results of HVAC measurements, heating case.

The resulting fresh air intake with insulated cabin was around 90 m^3/h, which is on the lower limit for keeping adequate air quality in the cabin. This means, that an air conditioning strategy of changing between fresh air and recirculation modes is not possible in these conditions.

The results show that with ca. -7 °C ambient temperature, the required heating power to keep the cabin at 23 °C is 3311 W. Using additional insulation this value decreases to 2886 W, 87 % of the original consumption. Using an additional air-air heat exchanger in combination with insulation, it further decreases to 2571 W, 78 % of the original case.

3.2 Cooling power

For cooling measurements, the following ambient and cabin conditions were applied:

- 40 °C ambient temperature,
- 28 °C set cabin temperature,
- 23 % ambient relative humidity,
- 2,2 l/min glycol-water coolant flowrate,
- 0 °C coolant temperature at water-air heat exchanger (evaporator) inlet.

Originally, the same 23 °C cabin temperature was set, but due to restrictions in the coolant circuit and the resulting low coolant flow rate, the cooling power was insufficient.

The results are summarized in the following table and figure.

Table 3: Results of HVAC measurements, cooling case.

Cooling Measurements, $T_{ambient}$ = 40 °C, T_{cabin} = 23 °C		
Cabin setup and HVAC mode	Consumption [W]	
Original, Fresh air	2482	100 %
Original, Recirculation	1787	72 %
Insulated, Fresh air	2276	92 %
Insulated Recirculation	1651	67 %
Original, Heat Exchanger	2394	96 %
Insulated Heat Exchanger	2125	86 %

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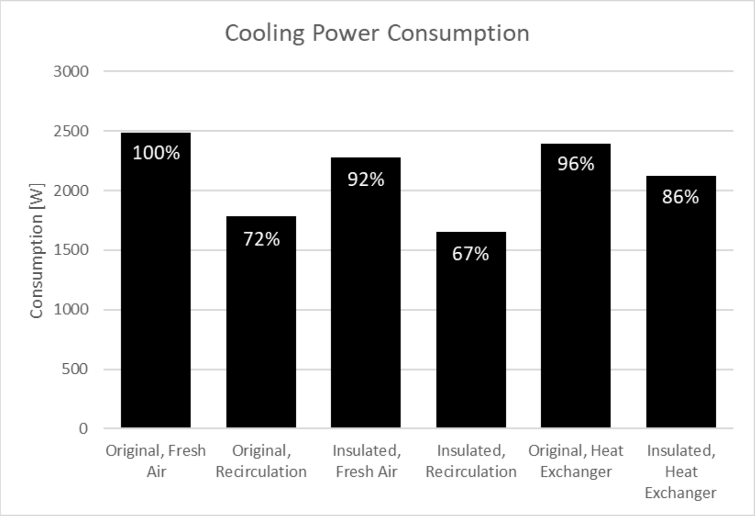

Figure 16: Results of HVAC measurements, cooling case.

The results show that with 40 °C ambient temperature, the required cooling power to keep the cabin at 28 °C is 2482 W. Using additional insulation this value decreases to 2276 W, 92 % of the original consumption. Using an additional air-air heat exchanger in combination with insulation, it further decreases to 2125 W, 86 % of the original case.

3.3 Planned measurements

In the heating case, additional measurements will be done after the installation of heating panels (chapter 8). This will enable the reduction of the cabin temperature while keeping comfort levels acceptable, which has a great potential of decreasing heating power demand.

The experimental cooling system will be revised to achieve higher cooling power output into the cabin, and the measurements will be repeated with 23 °C cabin temperature. The increased difference between ambient and cabin temperatures will also increase the beneficial effect of insulation and air-air heat exchanger.

These measurement results will be described in detail in Deliverable D4.4.

4 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is a chemical compound consisting of one carbon atom bonded to two oxygen atoms. It is a naturally occurring gas in Earth's atmosphere and plays a critical role in various biological and geological processes.

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4.1 CO_2 Phase diagram

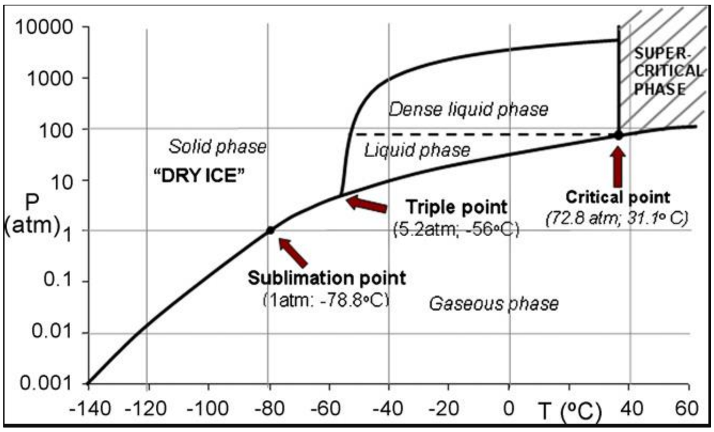

Figure 17: CO_2 phase diagram [1].

This is the phase diagram of carbon dioxide (CO_2). It illustrates in which state of aggregation (solid, liquid, or gaseous) CO_2 exists under different temperatures and pressures.

1. Three Main Regions:
   - **Solid state:** Top left in the diagram (low temperatures and low pressures).
   - **Liquid state:** Top right (higher pressures and moderate temperatures).
   - **Gaseous state:** Bottom left to right (high temperatures, low to moderate pressures).
2. Curves in the Diagram:
   - **Sublimation curve:** Separates solid and gaseous states. Shows the conditions under which CO_2 transitions directly from solid to gaseous (e.g., dry ice).
   - **Melting curve:** Separates solid and liquid states. Indicates the conditions for the transition from solid to liquid.
   - **Vaporization curve:** Separates liquid and gaseous states. Shows the conditions under which CO_2 transitions from liquid to gas.
3. Key Points:
   - **Triple point:** The point where solid, liquid, and gas coexist in equilibrium. For CO_2, it is at about -56.6 °C and 5.18 bar.
   - **Critical point:** The point where the boundary between liquid and gaseous states disappears. For CO_2, it is at about 31.1 °C and 72.8 bar.
4. Important Features of CO_2:
   - **Supercritical State:** When the temperature and pressure exceed the critical point, CO_2 exists in a supercritical state, possessing properties of both a liquid and a gas.
   - **Dry Ice:** At normal pressure, CO_2 sublimates directly from solid to gaseous, bypassing the liquid state.

4.2 Refrigerant R744

The role of CO_2 in refrigeration technology has gained significant importance in recent years. As a natural refrigerant, CO_2 (R744) offers notable advantages over fluorinated alternatives, being environmentally friendly, cost-effective, non-flammable, non-toxic, and colourless. It also serves as the reference standard for calculating the CO_2 equivalent of all refrigerants. R744 is classified under safety class A1 by ISO/ASHRAE, has a Global Warming Potential (GWP) of 1, an Ozone Depletion Potential (ODP) of 0, and is excluded from the phase-down requirements in the F-Gas Regulation[1]. According to the F-Gas Regulation, refrigeration systems with a CO_2 equivalent of 5 tonnes or less are exempt from mandatory leak tightness inspections, simplifying maintenance for systems operating at this capacity. While CO_2 may leak into the environment

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[1] EU-Rules: Guidance on the EU's F-gas Regulation and its legal framework (https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-rules_en)

during servicing, refilling, or decommissioning, costly recovery processes are unnecessary, further enhancing its practicality.

Despite these advantages, R744 presents technical challenges. These include a high operating pressure, a low critical temperature, dry ice formation when pressures drop below the triple point, and a very high standstill pressure. These characteristics necessitate precise engineering and careful selection of system components to ensure a safe and efficient operation.

In addition to its applications in traditional refrigeration systems, R744 is a promising alternative for the automotive industry. Vehicle air conditioning systems using CO_2 benefit from an environmentally friendly refrigerant. However, all system components must withstand pressures as high as 135 bar, a significant increase compared to the commonly used low-pressure refrigerant R134a. The superior thermodynamic properties of R744 strengthen its potential as a sustainable solution for automotive air conditioning systems, aligning with global environmental objectives.

5 Heat Pump

A heat pump is a system that extracts heat energy from a low-temperature source and elevates it to a higher temperature to make it usable for heating or hot water production. This is achieved through a thermodynamic process similar to how a refrigerator works in reverse.

5.1 Heat Pump Cycle

The operation can be divided into four main steps:

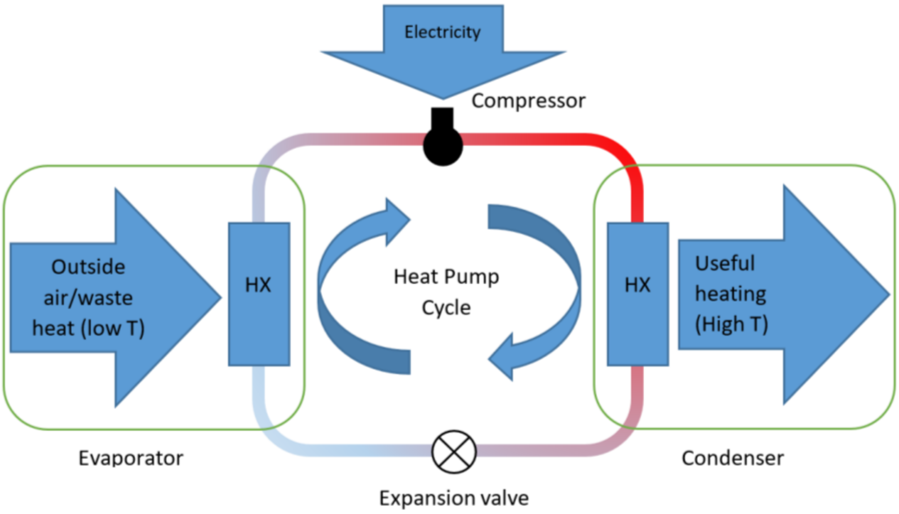

Figure 18: The heat pump cycle[2].

The cycle begins in the **evaporator**. Here, the liquid refrigerant vaporizes by absorbing heat from the surroundings (e.g., outdoor air). The **compressor** increases the pressure of the vaporized refrigerant, thereby raising its temperature. The hot refrigerant flows into the **condenser**, where it releases heat to the environment (e.g., to the interior of the car). The cooled refrigerant is then expanded through the **expansion valve** and flows back to the evaporator.

The heat pump has a **compressor** that compresses the refrigerant **R744**, from which heat is extracted and distributed. If more heat is required, there is an **HV Heater** located behind the radiator for supplemental warmth. Normally in E-vehicles the batteries are cooled via the **Chiller** (The electric motors are cooled by a separate circuit through the front cooler, there is no direct connection to the heat pump). For example, in the MEB-platform vehicles, there isn't a standalone heat pump unit; instead, it's referred to as a **"heat pump function"** that requires additional components, including control units, shut-off valves, mixing valves, and

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[2] https://automaticheating.com.au/complete-guide-to-heat-pumps/heat-pumps-explained/

heating condensers. Even in Q4 e-Tron vehicles without a dedicated heat pump, there is already a **heat exchanger (Chiller)** for the high-voltage battery. Additionally, two electric heating elements (PTC) are present: one directly integrated into the air conditioning system's distribution box in the dashboard, responsible for heating the vehicle interior, and the second one warms the coolant for the high-voltage battery as needed. The air conditioning system operates with two refrigerant circuits (for cooling the interior space and the high-voltage battery). In vehicles equipped with the **"heat pump function"**, both the Chiller and the second PTC are connected in parallel, allowing waste heat from both cooling circuits to be effectively utilized. Additionally, a mixing valve is installed for preheating the battery.

At an outside (ambient) temperature of 20 °C, the system has a stationary pressure of approximately 57 bar. The maximum pressure on the low-pressure side is 90 bar. The system pressures on the high-pressure side depend on the operating mode.

5.2 Functional principle – (MEB platform -Volkswagen)

5.2.1 Cooling

1.) The compressor compresses and heats the refrigerant.
2.) The gas cooler cools the refrigerant (while it's still in a gaseous state).
3.) The internal heat exchanger cools the refrigerant, causing it to become liquid.
4.) The refrigerant evaporates in the evaporator, extracting heat from the passing air.
5.) The partially liquid refrigerant flows through the internal heat exchanger and becomes gaseous (thereby cooling the refrigerant from the gas cooler).
6.) The compressor draws in the gaseous refrigerant.

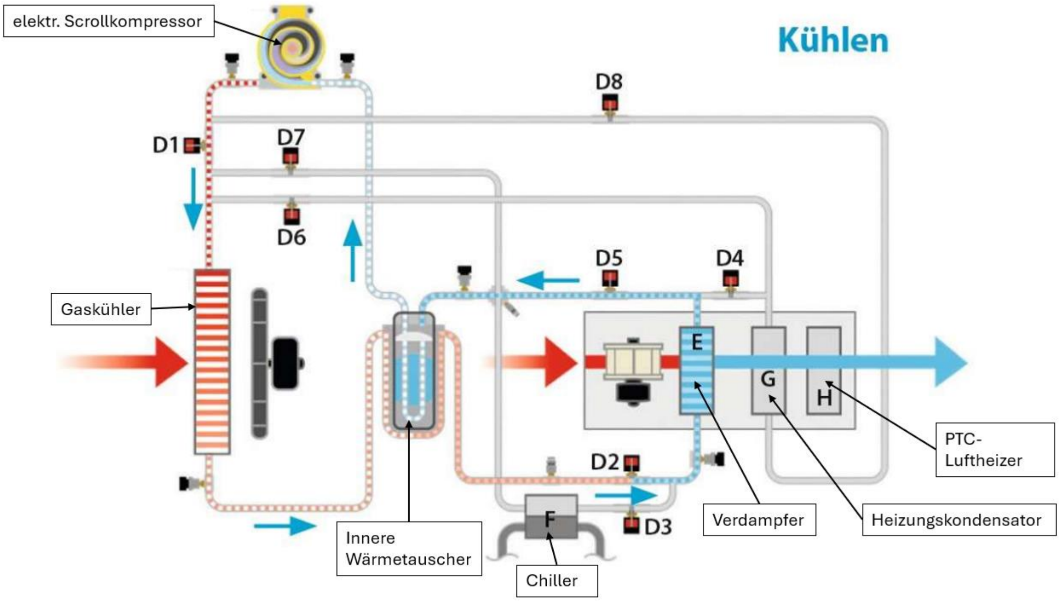

Figure 19: Cooling circuit of the VW heat pump system.[3]

5.2.2 Heating

1.) The compressor compresses and heats the refrigerant.
2.) The refrigerant flows through the heating condenser.
3.) The refrigerant flows through the evaporator (heating the incoming air with the condenser).
4.) The evaporator liquefies the refrigerant.

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[3] Die CO2-Wärmepumpentechnologie von Volkswagen (https://www.krafthand.de/artikel/die-co2-waermepumpentechnologie-von-volkswagen-57114/)

5.) The refrigerant flows through the internal heat exchanger to the gas cooler (the internal heat exchanger has no specific function here).
6.) The refrigerant becomes gaseous again in the gas cooler.
7.) The compressor draws in the gaseous refrigerant.

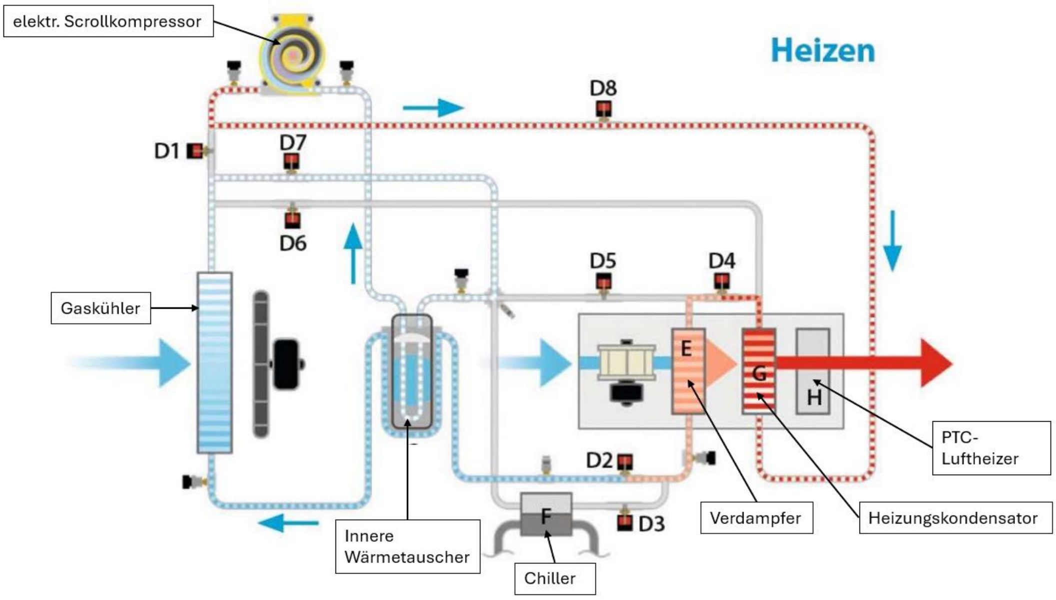

Figure 20: Heating circuit of the VW heat pump system.[3]

5.2.3 Reheat

1.) The compressor compresses and heats the refrigerant.
2.) The refrigerant flows through the heating condenser (thus giving off heat to the passing air).
3.) The refrigerant flows through the gas cooler.
4.) The internal heat exchanger slightly cools down the refrigerant.
5.) The evaporator cools the refrigerant.
6.) The refrigerant evaporates in the internal heat exchanger.
7.) The compressor sucks in the gaseous refrigerant.

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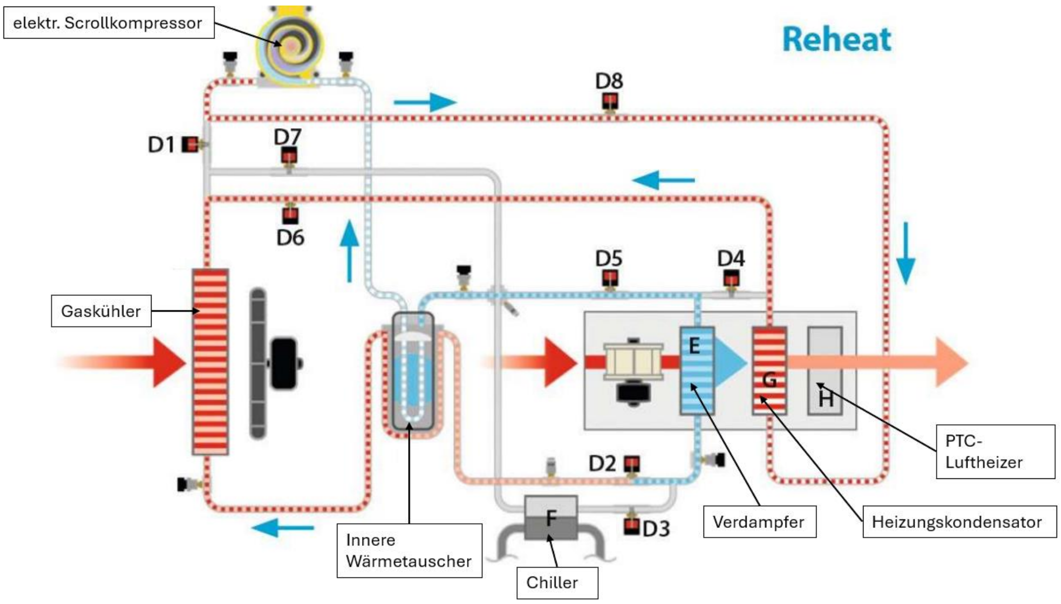

Figure 21: Reheat circuit of the VW heat pump system.[3]

5.3 Advantages of Heat Pumps

1. **Efficiency**: They typically deliver three to five times more heat energy than the electrical energy they consume (Coefficient of Performance, COP).
2. **Environmentally Friendly**: They use renewable energy sources and have low CO_2 emissions, especially when combined with green electricity.
3. **Versatility**: They can be used for both heating and cooling (e.g., in reversible systems).

5.4 Specific Features of a Heat Pump Using R744 Refrigerant

A heat pump using **R744** (carbon dioxide, CO_2) as a refrigerant has specific characteristics and features that distinguish it from heat pumps with conventional refrigerants (such as R410A or R134a). R744 is a natural refrigerant increasingly used in heat pump technology, particularly for applications with high demands on efficiency and environmental sustainability.

5.4.1 High Operating Pressure

- R744 operates at significantly higher pressures than conventional refrigerants. Typical operating pressures range between **80 - 120 bar** on the high-pressure side and **30 - 50 bar** on the low-pressure side.
- **Advantage**: These high pressures enable efficient heat transfer and compact components.
- **Disadvantage**: Specially designed, pressure-resistant components are required, which can increase material and manufacturing costs.

5.4.2 Transcritical Operation

- For R744, the critical point (temperature: 31.1 °C, pressure: 73.8 bar) lies within the range of typical operating conditions. Therefore, the heat pump often operates in the **transcritical range**.
    - **Subcritical**: The operation occurs below the critical point (similar to conventional refrigerants).
    - **Transcritical**: The operation occurs above the critical point. In this range, there is no phase change between liquid and gas, but the refrigerant exists in a supercritical state.

5.4.3 High Supply Temperatures

- R744 heat pumps can achieve **supply temperatures of up to 90 °C**, making them ideal for **domestic hot water** or for use in older heating systems with high temperature requirements.

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- **Advantage**: They are particularly efficient for hot water production (e.g., in domestic hot water systems or industrial heat applications).

5.4.4 High Heat Transfer Rate

- R744 has very good **thermal conductivity** and a high volumetric cooling capacity. This means that a relatively small amount of refrigerant can transport a large amount of heat.
- **Consequence**: Heat exchangers can be designed to be compact and efficient.

5.4.5 Sensitivity to Ambient Temperatures

- R744 heat pumps are particularly efficient at low outdoor temperatures, making them a good choice for regions with cold winters.
- However, efficiency decreases at high outdoor temperatures, as transcritical operation becomes less efficient.

5.4.6 Noise and Vibration

- Due to the high operating pressures and the transcritical process, R744 systems can potentially produce higher noise and vibration levels. Good design and sound insulation are therefore important.

Table 4: Summary of advantages and disadvantages of R744 as refrigerant

Advantages	Challenges
Environmentally friendly (GWP = 1, ODP = 0)	High operating pressures require robust components
High supply temperatures possible	Higher investment costs
Efficient at low ambient temperatures	Efficiency decreases at high outdoor temperatures
Compact components	Increased design complexity

6 Where is the R744 Refrigerant Used in Vehicles?

The refrigerant **R744 (CO_2)** is primarily used in **air conditioning systems** and **heat pump systems** in vehicles. It offers several advantages over traditional synthetic refrigerants like R134a or R1234yf, especially in terms of environmental sustainability and efficiency. Here are the main application areas and characteristics of R744 in vehicles:

6.1 Vehicle Air Conditioning Systems

R744 is increasingly used in air conditioning systems for **passenger cars** and **commercial vehicles**.

Reasons for Using R744 in Air Conditioning Systems:

- **Environmental Friendliness**: With a GWP of **1**, R744 is the most environmentally friendly refrigerant currently available for automotive air conditioning systems. It complies with the EU F-Gas Regulation, which bans the use of refrigerants with a GWP above 150 in new vehicles.
- **Efficiency**: R744 operates efficiently at higher ambient temperatures, making it ideal for air conditioning systems in vehicles often used across varying climates.
- **Safety**: Unlike some other alternatives (like R1234yf), R744 is **non-flammable** and thus safe to use.

Challenges:

- **High Operating Pressures**: R744 air conditioning systems require specially designed, pressure-resistant components due to their high operating pressures (up to 130 bar).
- **Cost**: The initial cost of R744 systems is higher due to the advanced technology and components required.

6.2 Vehicle Heat Pumps

R744 is also used in **heat pump systems** for electric vehicles (EVs) and hybrid vehicles to efficiently provide cabin heating.

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Special Advantages in Heat Pumps:

- **Efficient Heating at Low Temperatures**: R744 remains highly efficient even at very low outdoor temperatures, making it ideal for EVs in cold regions.
- **High Heating Capacity**: It enables rapid and effective cabin heating without significantly reducing the range of electric vehicles, as less electrical energy is needed.
- **Compact Design**: Thanks to its high volumetric cooling capacity, R744 heat pump systems can be designed to be smaller and lighter.

6.3 Applications in Commercial Vehicles and Buses

In **buses**, **trucks**, and other large vehicles, R744 is used for both air conditioning and heating systems. The advantages include:

- **High Cooling and Heating Capacity** for large cabin spaces.
- **Sustainability**: Particularly important in public transportation, where environmental regulations are stricter.

6.4 Advantages of Using R744 in Vehicles

1. **Regulatory Compliance**: Meets all current and future environmental regulations.
2. **Safe and Reliable**: Non-flammable, non-toxic, and widely available.
3. **Sustainability**: Helps automakers improve their CO_2 balance.

6.5 Comparison of fuel consumption when using R134a and R744

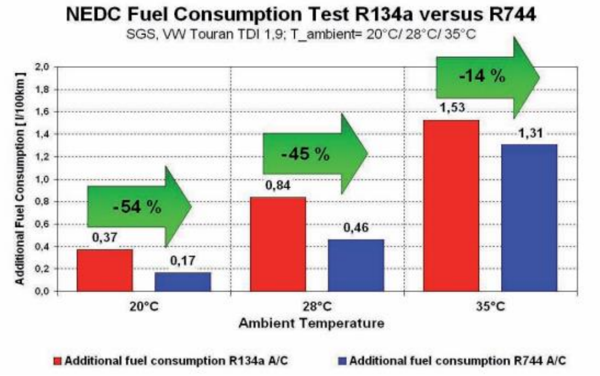

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Figure 22: Fuel consumption of an R134a MAC and an R744 MAC at different temperatures (UBA research project)[4].

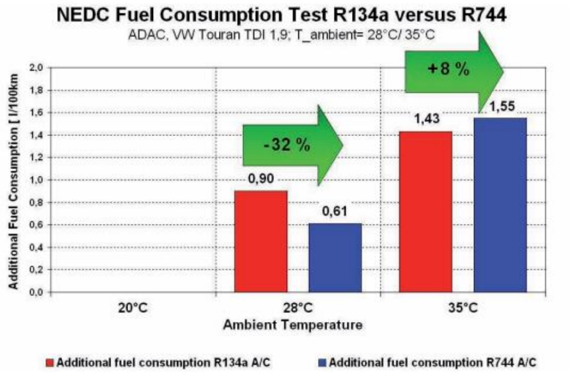

Figure 23: Fuel consumption of an R134a MAC and an R744 MAC at different temperatures (ADAC) [4].

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[4] Umweltbundesamt, Natural refrigerants – CO_2-based air conditioning system put to practical testing. https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3654.pdf

6.6 Outlook

The use of R744 in the automotive industry is expected to grow, particularly in Europe and other markets with stringent environmental laws. R744 air conditioning and heat pump systems are anticipated to become a standard in electric vehicles and sustainable mobility solutions.

7 EMPOWER HVAC concept

7.1 Schematic sketch of the actual HVAC circuit concept

Figure 24 shows the schematics of the current HVAC system of the IVECO truck working with the standard refrigerant R134a.

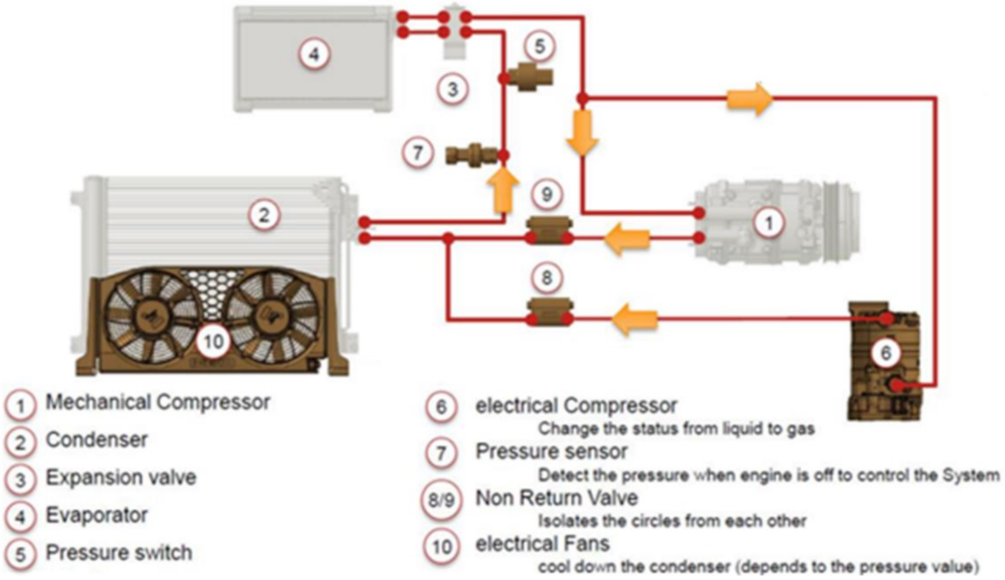

Figure 24: IVECO HVAC circuit (Source: IVECO).

For converting this circuit to one working with R744 the components must be changed, due to the widely different pressure levels. Also, some components must be added for the heat pump functionalities (see Figure 25).

The Accumulator with internal heat exchanger (4) needs to be added. The heating gas cooler (5) will be used instead of the radiator of the water circuit. The mechanical compressor will be removed. The water circuit will be completely removed and replaced with the R744 refrigerant circuit. The chiller (7) is used to release heat from the high-voltage batteries and the electric motors (optional).

7.2 EMPOWER HVAC 3D-Concept

1.) Fans
2.) A/C Heating gas cooler
3.) Evaporator
4.) Accumulator with internal heat exchanger
5.) Heating gas cooler (condenser)
6.) Compressor
7.) Chiller
8.) PTC heater

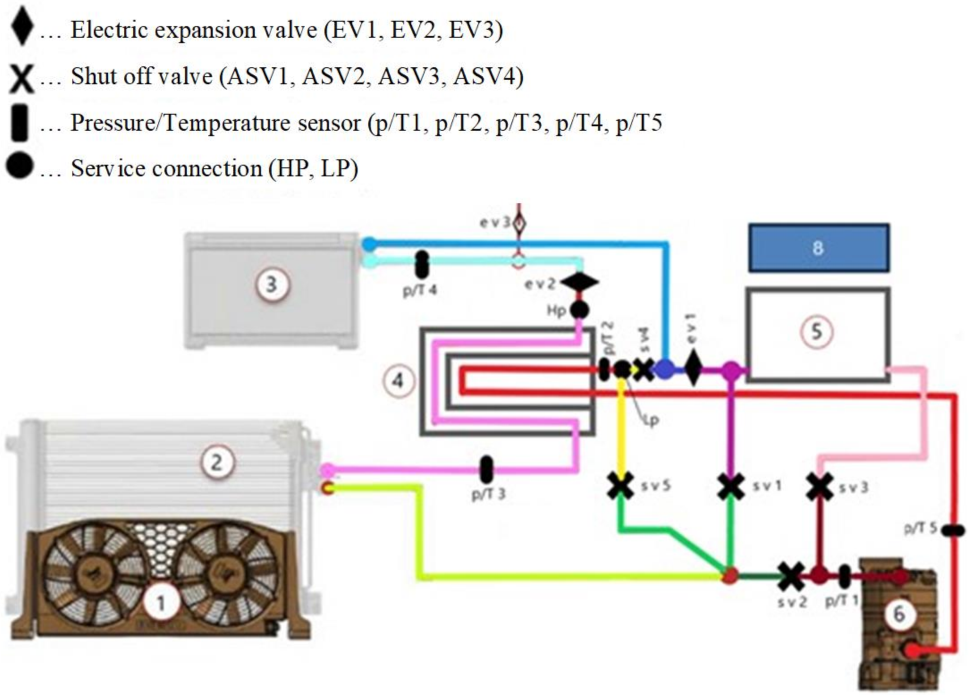

Figure 25: Schematic sketch of the EMPOWER HVAC circuit.

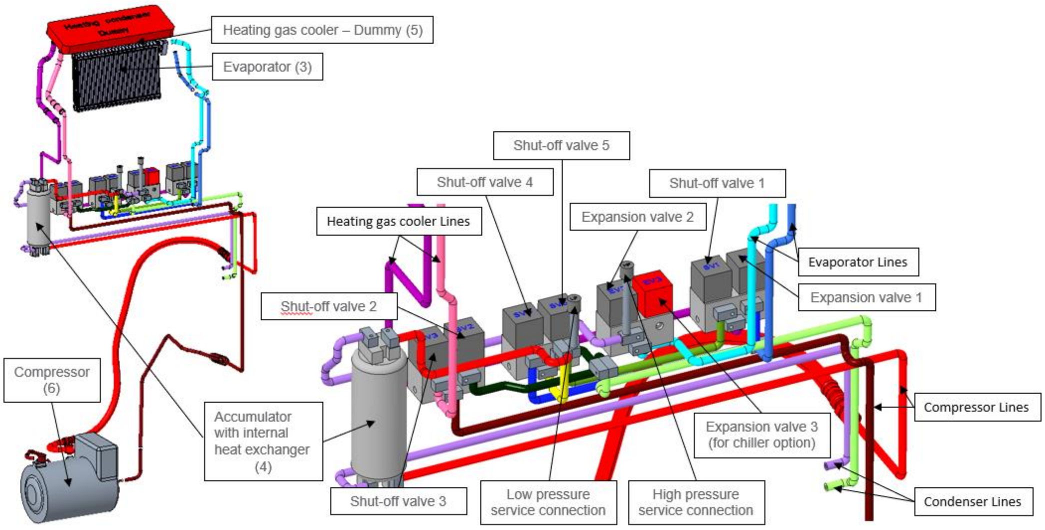

Figure 26: 3D sketch of the EMPOWER HVAC circuit.

7.3 System conditions for the HVAC circuit

7.3.1 Cooling

1.) The compressor heats the refrigerant.
2.) The gas cooler cools the refrigerant (while it’s still in a gaseous state).
3.) The internal heat exchanger cools the refrigerant, causing it to become liquid.
4.) The refrigerant evaporates in the evaporator, extracting heat from the passing air.
5.) The partially liquid refrigerant flows through the internal heat exchanger and becomes gaseous (thereby cooling the refrigerant from the gas cooler).
6.) The compressor draws in the gaseous refrigerant.

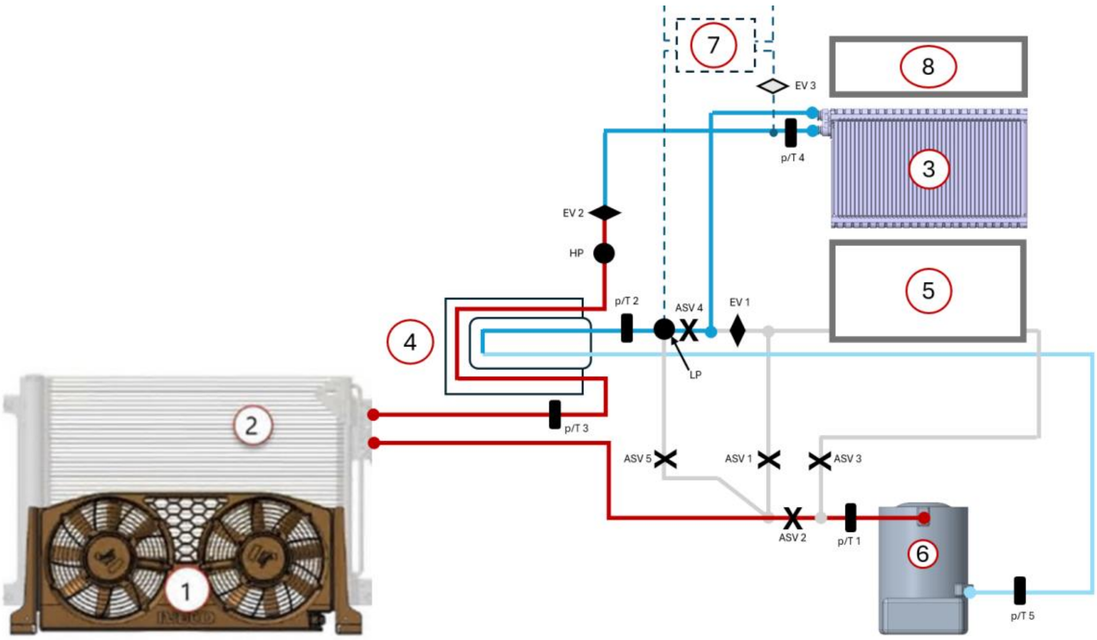

Figure 27: EMPOWER cooling circuit.

7.3.2 Heating

1.) The compressor heats the refrigerant.
2.) The refrigerant flows through the heating condenser.
3.) The refrigerant flows through the evaporator (heating the incoming air with the condenser).
4.) The evaporator liquefies the refrigerant.
5.) The refrigerant flows through the internal heat exchanger to the gas cooler (the internal heat exchanger has no specific function here).
6.) The refrigerant becomes gaseous again in the gas cooler.
7.) The compressor draws in the gaseous refrigerant.

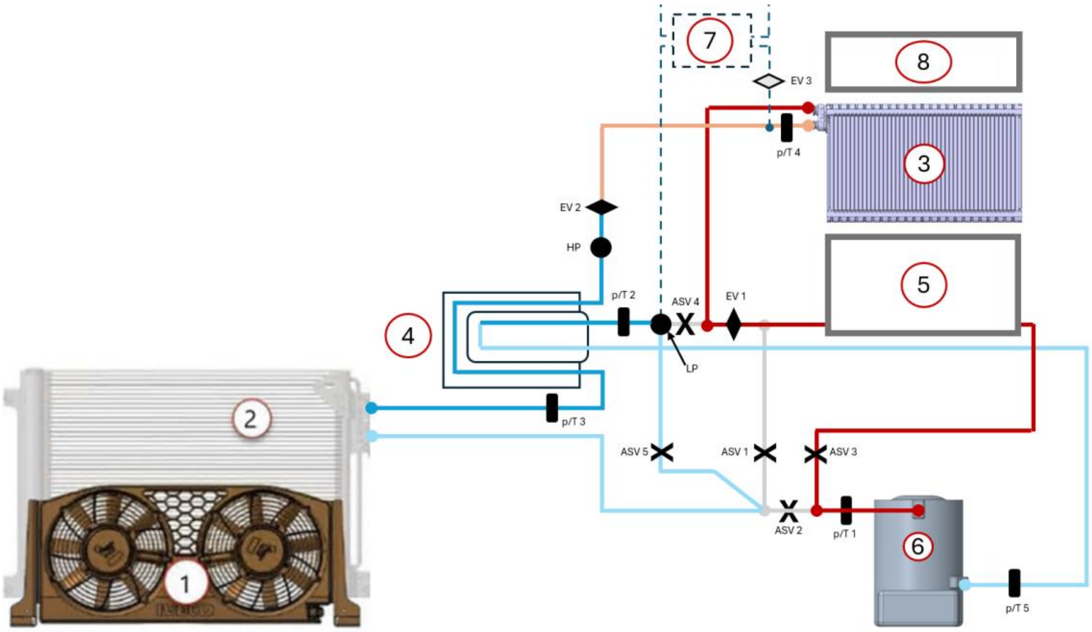

Figure 28: EMPOWER heating circuit.

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7.3.3 Reheat

1.) The compressor heats the refrigerant.
2.) The refrigerant flows through the heating condenser (thus giving off heat to the passing air).
3.) The refrigerant flows through the gas cooler.
4.) The internal heat exchanger slightly cools down the refrigerant.
5.) The evaporator cools the refrigerant.
6.) The refrigerant evaporates in the internal heat exchanger.
7.) The compressor sucks in the gaseous refrigerant.

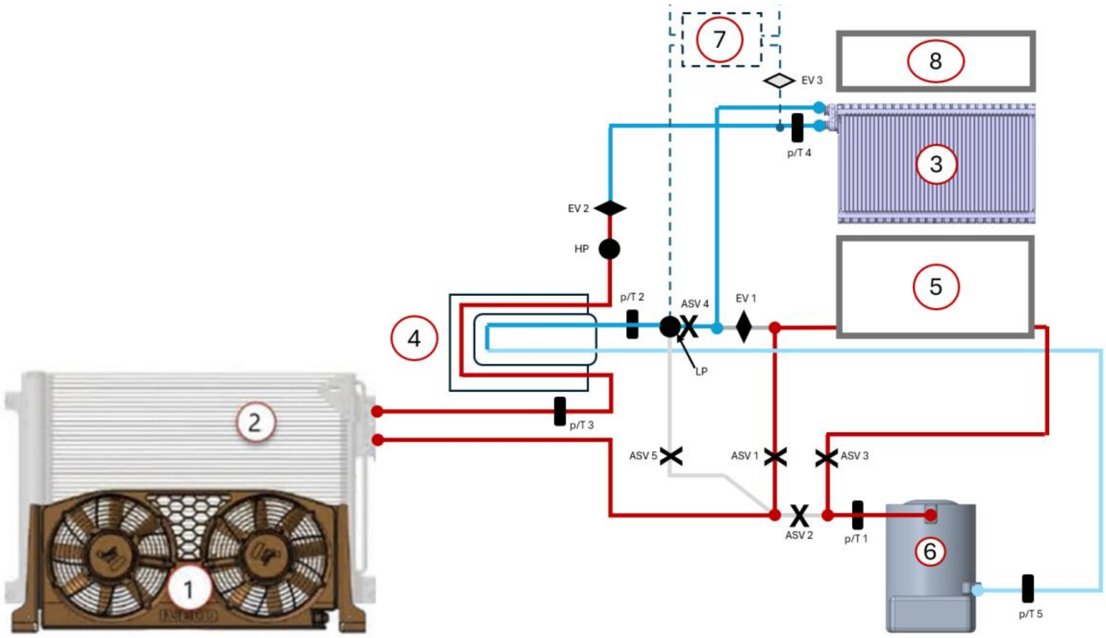

Figure 29: EMPOWER reheat circuit.

7.3.4 Safety valves

There are three high-pressure safety valves in the heat pump system:

1.) At the compressor on the high-pressure side
2.) For the evaporator on the valve block on the low-pressure side
3.) For the accumulator/dryer, also on a valve block on the low-pressure side

The 2nd valve on the evaporator block is needed because the evaporator is also used for heating. This requires high pressure. The valve protects the evaporator from overpressure if the regulation does not work properly or if a valve jams. The valve on the high-pressure side opens at a pressure of 160 bar (up to max. 170 bar) and closes again when the pressure has decreased (at approximately 150 bar). The valve on the low-pressure side opens at a pressure of 120 bar (up to max. 130 bar) and closes again when the pressure has decreased (at approximately 110 bar).

7.3.5 Valve circuit

Table 5: Valve conditions of the HVAC circuit.

Valves	Cooling Phase	Reheating Phase	Heating Phase
SV1	closed	open	closed
SV2	open	closed	closed
SV3	closed	open	open

SV4	open	open	closed
SV5	closed	closed	open
EV1	closed	closed	X
EV2	X	X	X
EV3	closed	closed	closed

The initial heating phase is slightly sluggish, so support from the PTC air heater may be needed.

The reheat phase is used in situations such as a fogging windshield or if the incoming fresh air has extremely high humidity. The Expansion valve 3 is for the chiller option.

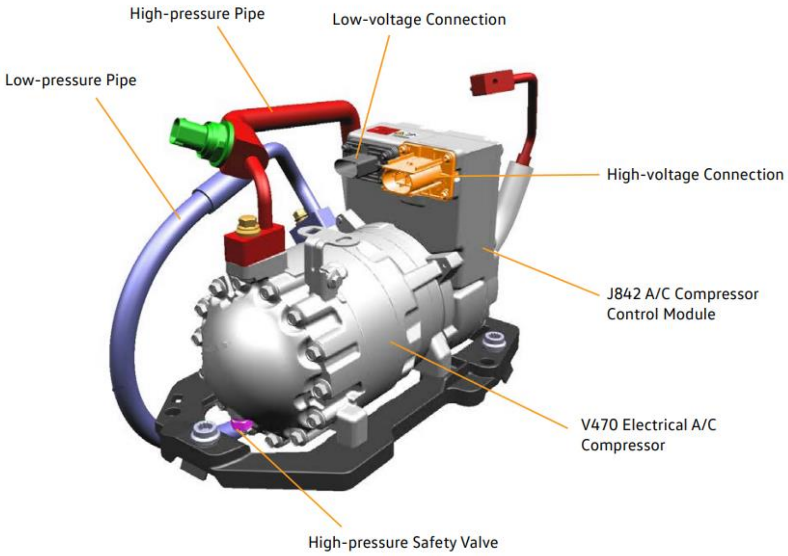

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Figure 30: 3D model of the compressor.

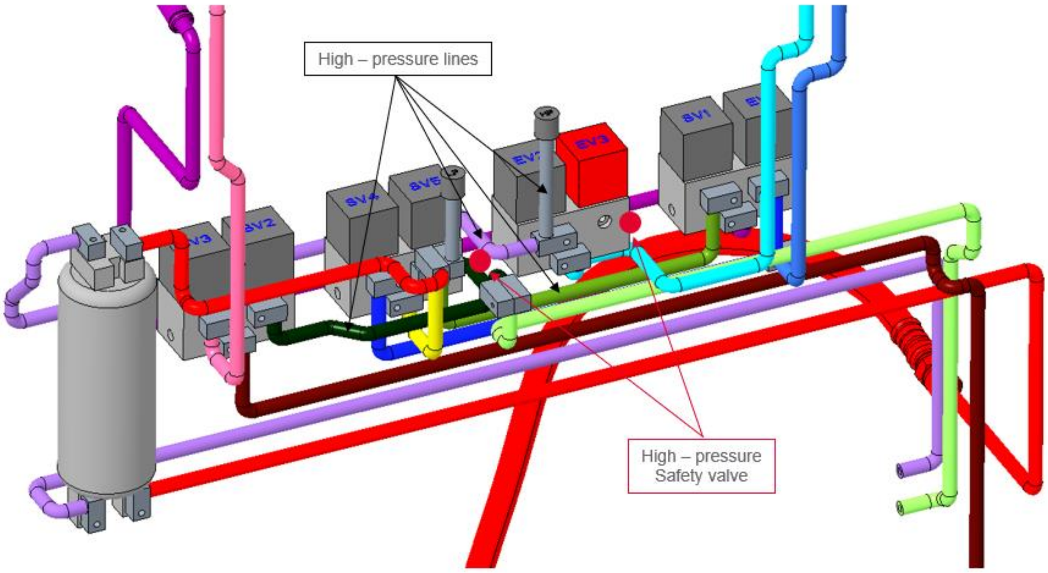


Figure 31: Valve control unit.

7.3.6 Pipes of the EMPOWER HVAC system

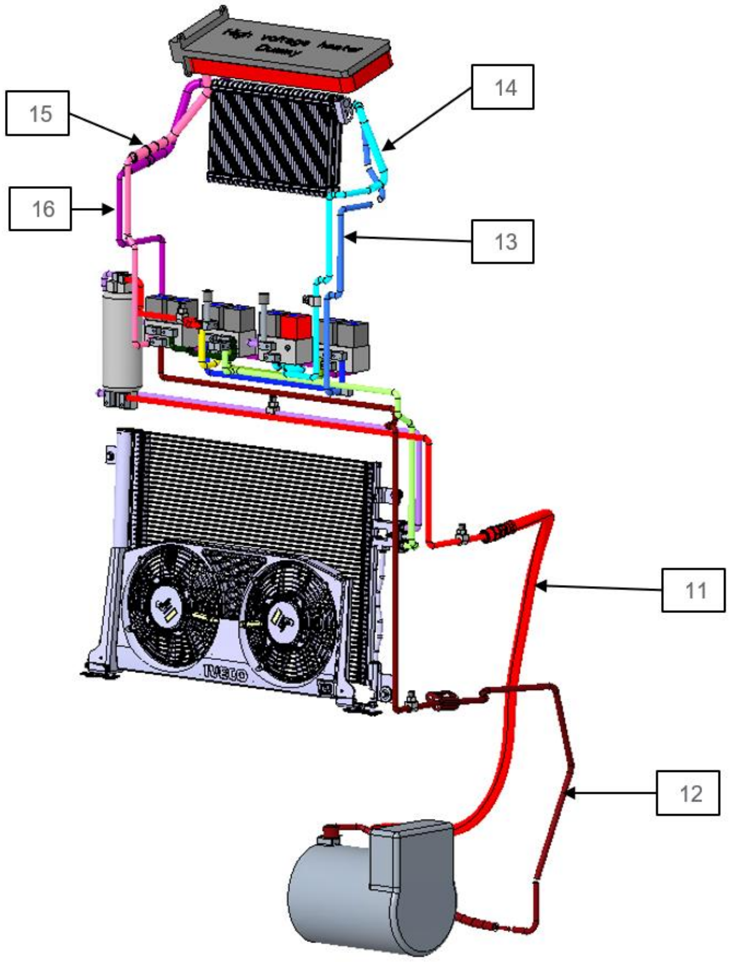


Figure 32: Pipes of the EMPOWER HVAC system.

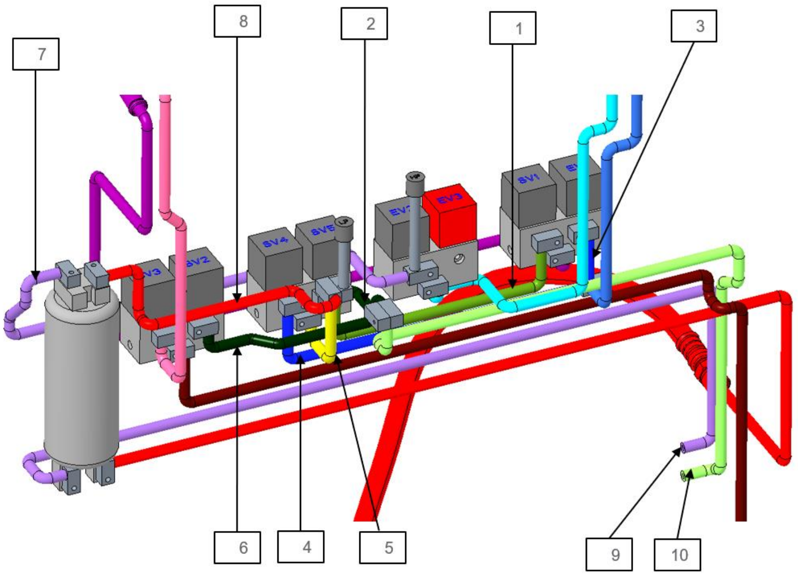


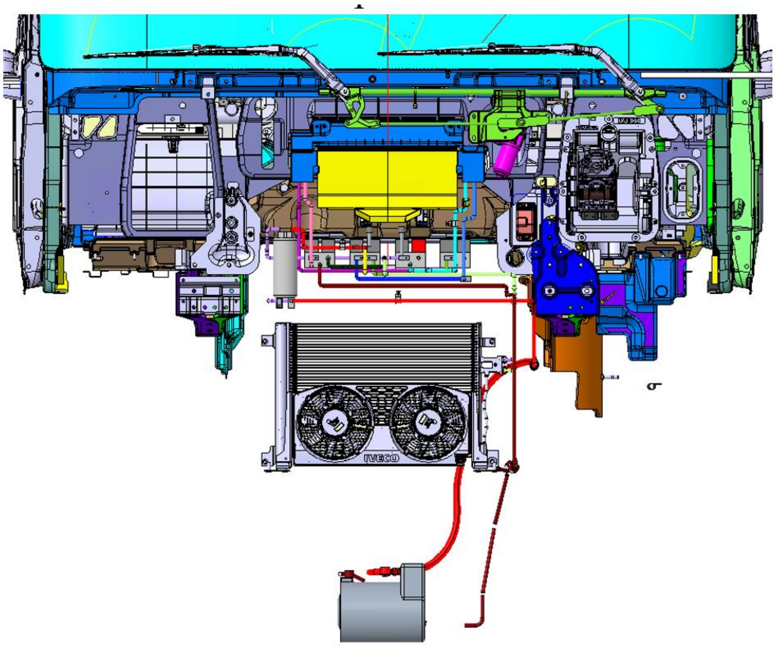
Figure 33: Pipes of the EMPOWER HVAC system (valves).

7.3.7 Part list of the pipes

Table 6: List of pipes needed for the EMPOWER HVAC system.

Pipe Nr.	Position
Pipe 1	between SV1 and SV5
Pipe 2	between SV5 and Block 3/ Block_T
Pipe 3	between EV1 and Block_T_1
Pipe 4	between Block_T_1 and SV4
Pipe 5	between SV4/SV5 and Block_T_2
Pipe 6	between SV2 and Block_3/Block_T
Pipe 7	between EV2 and Accumulator
Pipe 8	between Block_T_2 and Accumulator
Pipe 9	between Accumulator and Condenser
Pipe 10	between Condenser and Block_3/Block_T
Pipe 11	between Accumulator and Compressor
Pipe 12	between Compressor and SV3/SV2
Pipe 13	between Evaporator and Block_T_1
Pipe 14	between Evaporator and EV2/EV3
Pipe 15	between SV1/EV1 and gas cooler
Pipe 16	between gas cooler and SV3

7.3.8 Model of the EMPOWER HVAC installation



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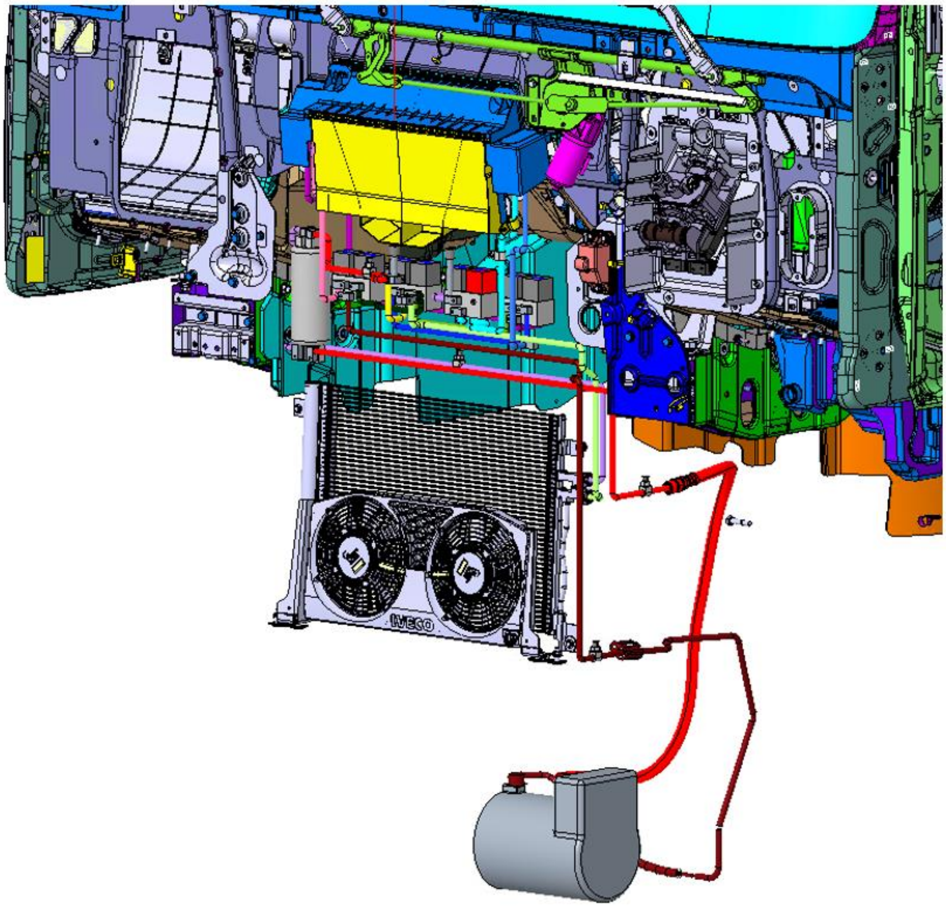

Figure 34: 3D model of the EMPOWER HVAC installation.

7.4 Heat pump components for EMPOWER system

7.4.1 Air conditioning compressor – Hanon systems 1EA 820 808 E

Figure 35: Air conditioning compressor.[5]

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[5] Volkswagen Group of America, Self-Study Program 881213 - Air Conditioning and Heat Pump in MEB Vehicles, 2021.

Table 7: Technical data of air conditioning compressor

Parameter	Quantity
Stroke volume	5.3 cm^3
Refrigerant	R744
Communication	via LIN-Bus
Motor type	Permanent magnet - synchronous machine
Max. motor power	4.4 kW
Max. compressor power consumption	5.5 kW
Functional engine speed range	600 - 8600 rpm
Nominal input voltage	400 V
Functional voltage range	195 - 470 V
Ambient temperatures	A/C mode possible from -28 °C to 70 °C communication possible from -40 °C to 70 °C
Total oil filling quantity	200 cm^3
Pressure relief valve with discharge detection	Installed in accordance with SAE standard J639, discharge pressure at approximately 160 bar, closing pressure at approximately 140 bar

7.4.2 Accumulator / dryer and internal heat exchanger – Hanon Systems 1EA 816 582

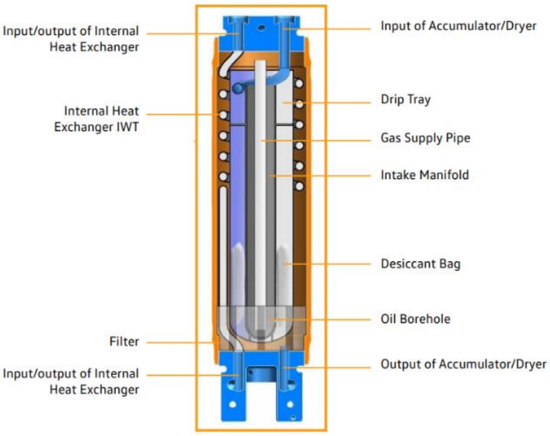

Figure 36: Accumulator / dryer and internal heat exchanger.[5]

7.4.3 High-Voltage heater (PTC) – Valeo 1EA 963 581 F

The PTC heater has an operational range between 0 to 6 kW.

Figure 37: PTC heater.[6]

7.4.4 Condenser / Gas cooler - 1EA 816 515 A

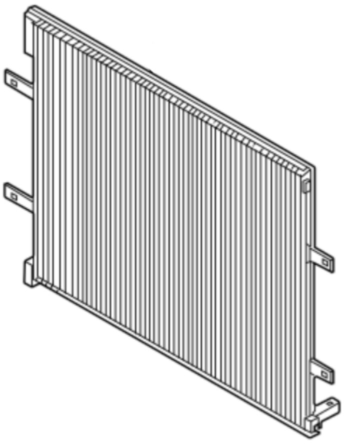

Figure 38: Condenser / Gas cooler.[7]

7.4.5 Evaporator Core – 1EA 816 103 D

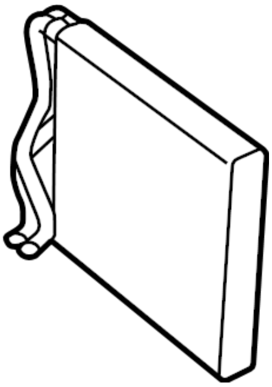

Figure 39: Evaporator core.[8]

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[6] www.ebay.at/itm/265735474089

[7] https://parts.vw.com/Volkswagen__ID4/HVAC.html

[8] https://parts.vw.com/Volkswagen__ID4/HVAC.html

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7.4.6 Valves – Hanon Systems

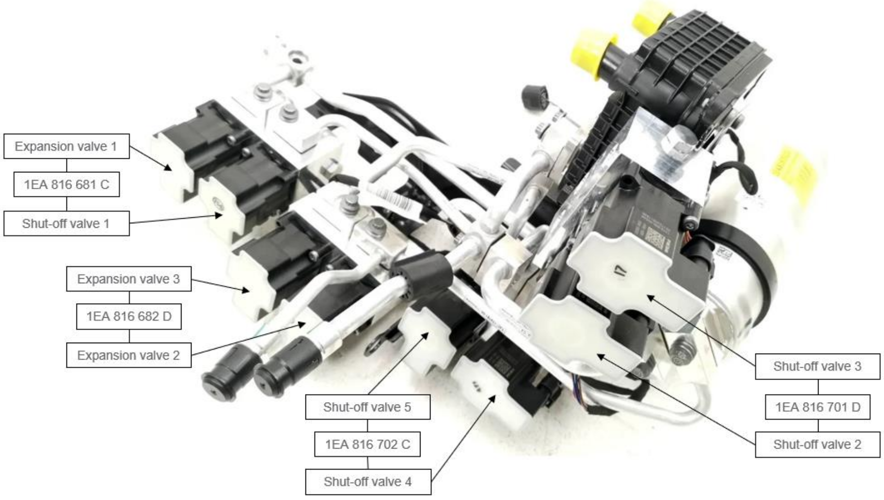

Figure 40: Valves control unit.

7.4.7 Chiller – Valeo 9J1 816 132

The chiller is used to release heat from the high-voltage batteries. The chiller is optional in EMPOWER. The use of this is still evaluated.

Figure 41: Chiller.

7.4.8 Refrigerant lines

The flexible hose line structure comes in two versions.

The single hose line contains refrigerant and refrigerant oil seals, along with a resistant interior layer (for instance, the low-pressure hose). This is encased by a fabric jacket, which fortifies the hose against pressure. Additionally, there is the part that is visible to us – the external layer.

The configuration of the hose lines on the high-pressure side is distinct. Owing to the intense heat from the hot gas, these hose lines also contain a metal-plated corrugated tube internally. Additionally, these hoses have a specific bending radius limitation and must not be sharply bent or twisted.

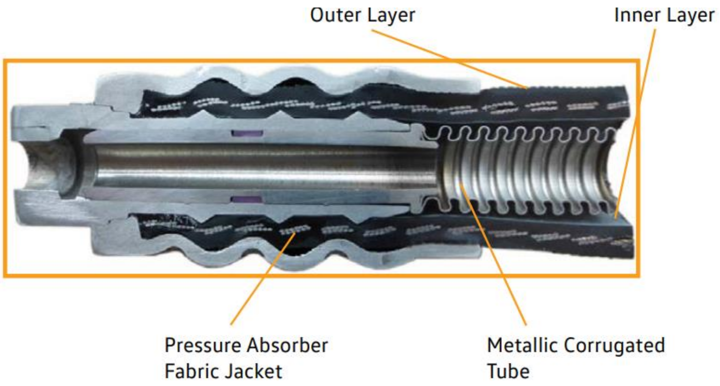

Figure 42: Section of a high-pressure line.[9]

8 Heating Panels

The interior heating system to be developed under the framework of project EMPOWER will consist of electrically heated surfaces providing infrared radiation (IR) heat rather than a system warming the cabin air. The system relies on electrically conductive coatings that are integrated into the structure of certain vehicle interior parts, generating heated surfaces that are characterized by a quick heat-up process and high heating efficiency.

In the case of electric vehicles, where no waste heat from the engine is available, an energy efficient method for heating the vehicle interior which does not deplete battery capacity must be found. Heated surfaces generally provide a more efficient way of heating compared to hot-air systems, conserving energy for driving range.

The IR heating elements will be installed on the structural interior parts, underneath the finishing material. Depending on the utilized material configuration, the heaters are characterized by a total thickness of 0.5 – 1 mm. Through their minimal space requirements, there are numerous options for system design. A system layout with large-area heaters, capable of warming the cabin within a few minutes after activation was designed. The heaters will be laid out for an input voltage up to 50 V and to a sheet resistance of 3.65 Ω.

The main components to be heated will be the door panels on the driver and passenger side, the floor between driver and passenger, the glove box cover, the floor of the driver and the passenger, and the rear wall of the bunk bed compartment in the back of the cabin. Depending on the gathered results during testing, the steering wheel and the ceiling may be equipped with heaters as an additional option. Figure 43 shows the outlines of the heating panels and Figure 44 shows the placement of each heating panel in a 3D sketch of the cabin.

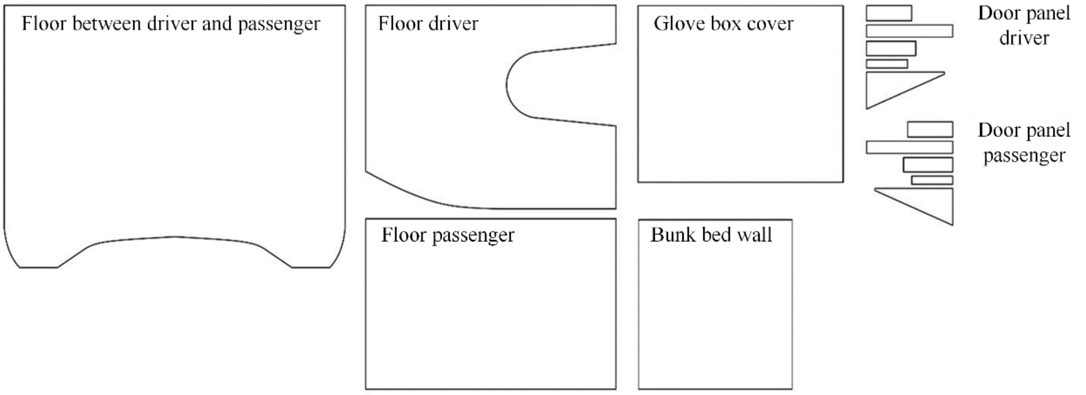

Figure 43: Heating elements layout – outer contours of heating elements.

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[9] Volkswagen Group of America, Self-Study Program 881213 - Air Conditioning and Heat Pump in MEB Vehicles, 2021

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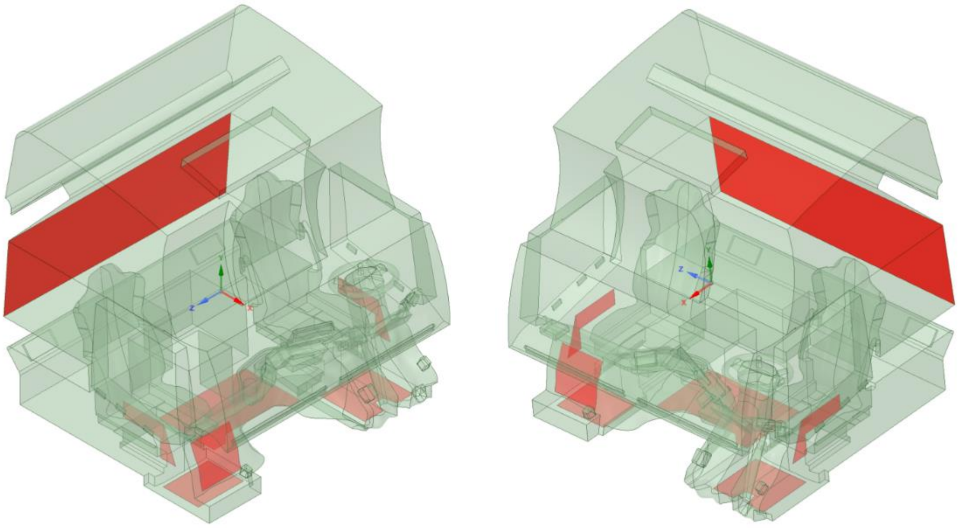

Figure 44: Sketch of the heating panel placement in the cabin.

It will be safeguarded, that the IR heating elements are compatible with the surfaces they are applied to as well as with the specialized adhesives that are going to be used in order to attach them securely without compromising flexibility or longevity. The electrical connections are integrated into the vehicle's wiring harness.

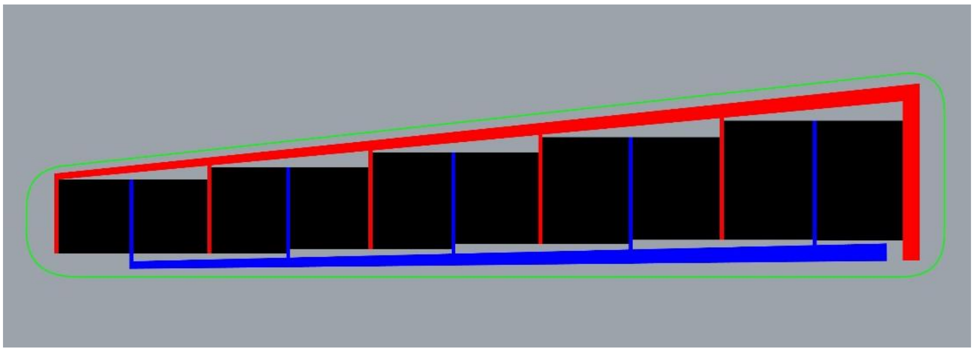

Figure 45: Example IR heating element layout in CAD software.

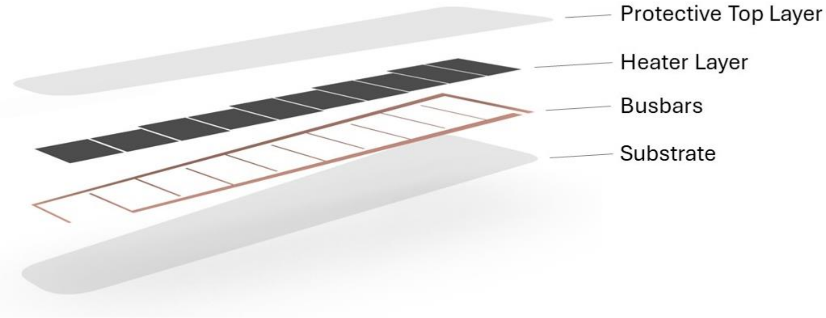

Figure 46: Example IR heating element buildup.

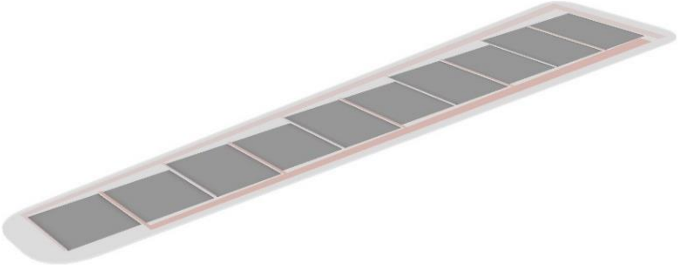

Figure 47: Example IR heating element (arm rest heater).

9 Conclusions

Different improvements on the state-of-the-art truck cabin were performed and then measurements were conducted in a climatised chamber. On one hand the heating case was tested, and on the other cooling scenarios with high ambient temperature and additional simulated solar radiation were performed.

The results show that with an ambient temperature of -7 °C, the required heating power to keep the cabin at 23 °C is 3,311 W. Using additional insulation this value decreases to 2,886 W, which is 87 % of the original consumption. Using an additional air-air heat exchanger in combination with an improved insulation, the heating power further decreases to 2,571 W, which is approx. 78 % of the original case.

Furthermore, the results in the cooling case show that with an ambient temperature of 40 °C, the required cooling power to keep the cabin at 28 °C is 2,482 W. Using additional insulation this value decreases to 2,276 W, 92 % of the original consumption. Using an additional air-air heat exchanger in combination with insulation, the cooling power further decreases to 2,125 W, which is about 86 % of the original case.

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10 Bibliography

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5	**POLITO**	Politecnico di Torino	IT
6	**LT**	Lead Tech SRL	IT
7	**VIL**	Villinger GmbH	AT
8	**CID**	Fundación CIDETEC	ES
9	**CTE**	CT Engineering GmbH	AT
10	**GLO**	GRUBER Logistics S.p.A.	IT
11	**BRE**	BREMBO SPA	IT
12	**IIT**	Istituto per Innovazioni Tecnologiche Bolzano S.c.a.r.l.	IT
13	**ALFI**	Air Liquide	FR
14	**FMF**	FPT Motorenforschung AG	CH