Energy efficient & comfortable cabin heating

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Abstract Battery electric vehicles become an increasingly interesting alternative to conventional vehicles with combustion engine as the costs decrease and the driving range improves. Although, the significant decrease of the driving range at very hot or cold ambient temperatures is still an issue that needs to be solved in order to further improve the adoption of battery electric vehicles. In this chapter a system for energy efficient cabin heating consisting of a heat pump system, a so-called smart seat and radiation heating panels is presented. By means of simulations the possible reduction of energy consumption and increase of driving range during an NEDC is evaluated.

Introduction

The power demand of air conditioning systems at very hot or cold ambient temperatures significantly decreases the driving range of battery electric vehicles at these conditions. At winter conditions the driving range may drop by 30-50 % (see e.g. [1]) because of the high power demand of resistance heaters and the decreasing efficiency of lithium-ion batteries. Thus, innovative solutions for the heating of the passenger compartment are needed. In the EU-funded research project „OPTEMUS“ a solution with a compact refrigeration unit, that enables heat pump operation, a “smart seat” with integrated Peltier elements and radiation heating panels has been developed. This system significantly reduces the energy consumption for heating the passenger compartment and increases the driving range of electric vehicles.

Thermal comfort assessment

In order to enable a fair comparison of different heating technologies in terms of energy consumption, equal thermal comfort needs to be ensured. As different heating technologies use different heat transfer paths (thermal convection with the heat pump system, thermal conduction with the seat heating and thermal radiation with the radiation heating panels) a thermal comfort assessment method that considers all of them was required. The so-called Predicted Mean Vote (PMV) model, developed by P.O. Fanger [2], is one of the most recognized thermal comfort models and was used for the comfort assessment. Its comfort index ranges from -3 (cold) to +3 (hot) and is depending on six calculation factors, which are shown in **Fig. 5**.

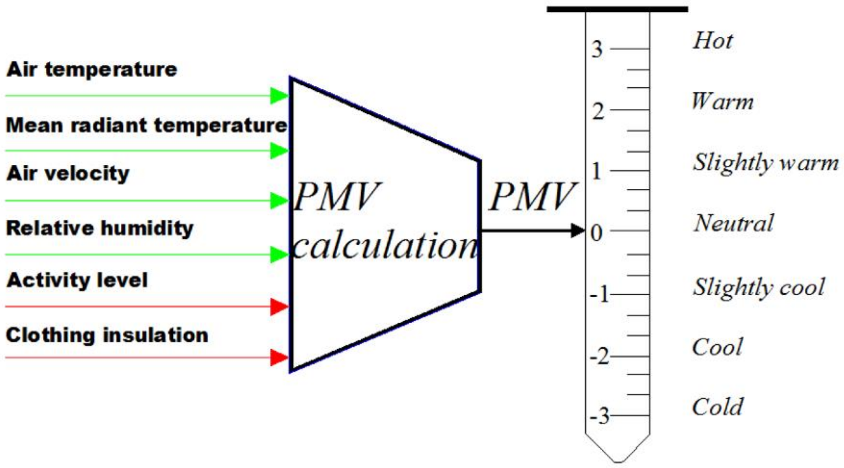

Fig. 1 Scale and calculation factors of PMV index [1]

The PMV is linked to the Predicted Persons Dissatisfied (PPD) with the following equation:

$$PPD = 100 - 95\, e^{-0.03353\, PMV^4 - 0.2179\, PMV^2}$$

This leads to the fact that at a PMV of +3 (hot) or -3 (cold) 99 % of occupants feel thermal discomfort. A PMV equal to zero, which represents thermal neutrality, leads to 95 % of occupants that feel thermal comfort and only 5 % discomfort (**Fig. 2**).

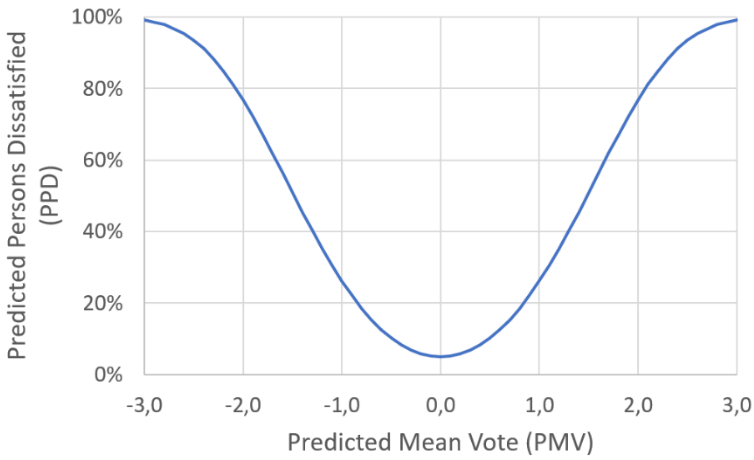

Fig. 2 Predicted Persons Dissatisfied (PPD) depending on Predicted Mean Vote (PMV)

For a comparison of different heating technologies in terms of energy consumption a PMV of zero was used as a constraint.

Heat Pump System with the Compact Refrigeration Unit

For an efficient heating of the cabin inlet air a heat pump system was used. Its core part is the compact refrigeration unit (CRU) from DENSO using a natural refrigerant. It is a so-called water-to-water system that consists of a compressor, two plate heat exchangers and an expansion valve. All components are integrated in the same housing (**Fig. 3**).

Fig. 3 Compact Refrigeration Unit (CRU)

Inside the evaporator (chiller) heat is transferred from the coolant circuit to the refrigeration cycle and consequently cooling down the coolant. This amount of heat increased by the heat of the compressor is transferred to a second cooling circuit inside the condenser, with the effect of heating up the coolant. The two emerging temperature levels can be used for the thermal management in the vehicle in order to combine heat sources and heat sinks in an energy efficient way. Therefore, the system depicted in **Fig. 4** was used to divert the coolant flows to various components of the electric vehicle to enable different operation modes. These operation modes are cooling, heating and dehumidification of the passenger cabin, battery heating and cooling as well as powertrain heating and cooling. **Fig. 4** shows an operation in heat pump mode, where the passenger cabin is heated and the ambient air is used as heat source. By using the ambient air as heat source a coefficient of performance (COP) of 1.50 could be achieved at 0 °C and a COP of 2.67 at +10 °C for cabin heating during NEDC.

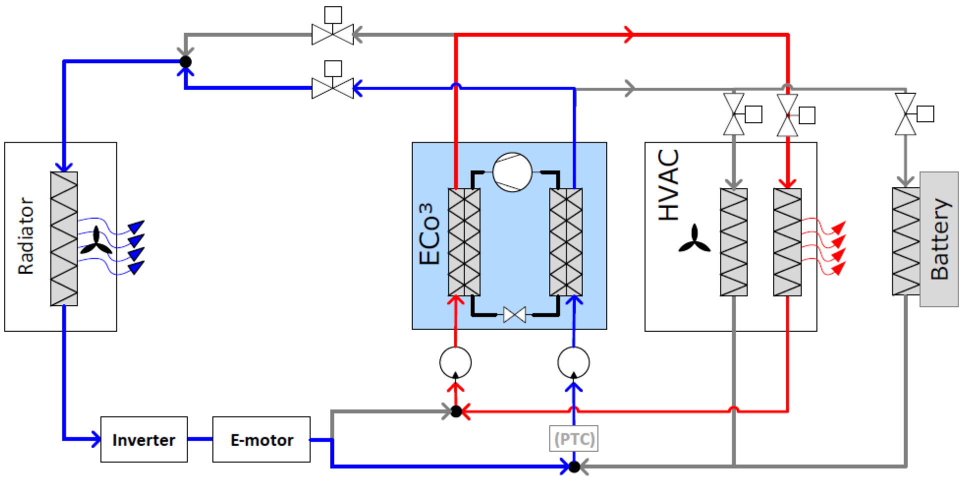

Fig. 4 Thermal management system for an electric vehicle (heat pump mode)

Radiation Heating Panels

Conventional heating, ventilation and air conditioning (HVAC) systems only rely on the convective heat transfer where air is conditioned before entering the passenger cabin. These systems offer a simple implementation into a vehicle and a simple possibility to use waste heat from combustion engines, but also show considerable disadvantages when assessed in regard to energy efficiency in electrified vehicles. Especially in “fresh air mode” the energy demand is high due to the fact that heat losses are caused by the warm air exiting the cabin which need to be compensated by heating up the cold air before entering the passenger cabin. In addition to the air also the coolant and the heater core need to be heated up as well. These thermal inertias cause only little impact during long distance use cases. Considering urban electric vehicles with primarily short trips, lowering thermal inertias inside the HVAC system offers potential for improving the energy efficiency. As discussed in [3], radiation heating panels offer a possibility to increase heating efficiency and passenger comfort at the same time. While Pingel et al. [3] propose a far infrared surface heating system, the state of the art also considers infrared heating systems with higher temperatures [4]. Both heating systems are not meant to replace the conventional HVAC system entirely, but to reduce its energy demand. As shown in **Fig. 1**, thermal comfort is depending on a variety of factors. So, if the mean radiant temperature of surrounding surfaces can be increased by radiation heating, the air temperature may be decreased. Radiative heat is transferred as electromagnetic radiation and the wavelengths depend on the surface temperature of the emitter. Radiation heating systems can be considered as long, mid and short wavelength infrared, with increasingly higher temperatures of the emitter. As no consistent terminology for these heating systems exists, especially solutions using shorter wavelengths are often called infrared heaters. Other solutions, which also emit infrared radiation on lower temperature levels and thus longer wavelengths are often called surface heating systems. Surface heating systems cover relatively large areas and emit radiation at temperatures below 70 °C in order to prevent damages to the skin. Both radiation heating systems may be used for vehicle passenger cabins. In the Fiat 500e demonstrator vehicle a surface heating system was applied on different surfaces close to the driver and the co-driver. **Fig. 5** shows a simulation of surface temperatures of the car interior at -10 °C ambient temperature. All radiation panels were set to a constant surface temperature of 47 °C for the transient simulation of the cabin heat up, not considering the fast heat up of the panel itself.

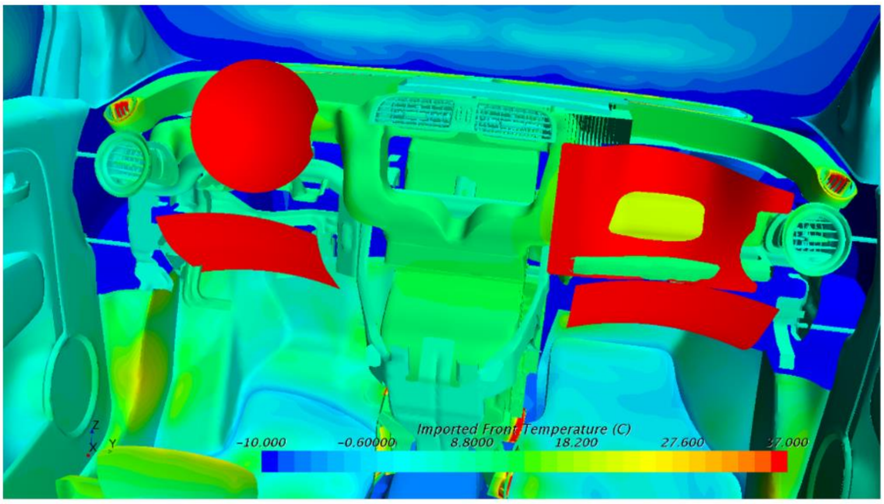

Fig. 5 Simulation of surface temperatures of the car interior at -10 °C ambient temperature

The simulation was set up with a “virtual comfort dummy” inside the cabin and considering thermal radiation transferred from the panels to the passenger by means of view-factors. With a total electrical panel power of 100 W the air temperature could be lowered by 3 K for quasi-static operating conditions in heating mode while maintaining the same comfort level.

Smart seat

The smart seat was designed to cool or heat the passenger by direct contact depending on the climate conditions. This is achieved by the combination of thermoelectric elements (Peltier elements) and five thermally conductive layers within the smart seat specifically at the areas with direct contact with the driver/passenger. The advantage of using the seat for heating and cooling is the reduction of air temperature inside the cabin, which thus will reduce the energy consumption of the heat pump system ensuring same comfort. In order to avoid local discomfort, the heat flow should be limited to approx. 60 W/m^2 [5, 6] for the heating case. Moreover, lower body regions (e.g. thigh, foot etc.) should be warmer than the upper body regions (e.g. arm, chest etc.) [6]. Consequently the control of the smart seat has been designed accordingly. The adaptive control theory (fuzzy logic) has been applied to regulate the comfort of the user based on the PMV model. Two main aspects should be carefully considered: i) cloth resistance estimation and ii) heating and cooling by direct contact. ISO 9920 standard [7] establishes the method for measuring the coverage index (cloth resistance). However, this mathematical method cannot be applied to calculate it online, since the variables used to calculate it are passenger dependent (i.e. are purely stochastic variables). For this reason, an artificial intelligence algorithm has been implemented taking as input variables the ambient temperature and the relative humidity measured when the user switches on the system. Then, by measuring the temperature increase of the smart seat in during 5 seconds of operation, the cloth resistance is predicted. **Fig. 6** shows the numerical simulation of the smart seat integrated in the Fiat 500e interior after 10 min of warm up at -10 °C ambient temperature with focus on driver's seat. It can be clearly observed the localized areas of the seat which are heated for the thermal comfort of the driver.

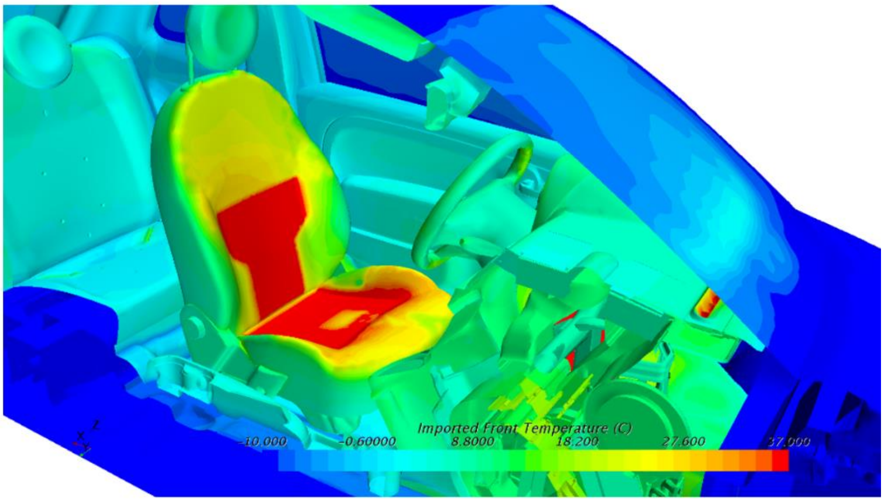

Fig. 6 Simulation of surface temperatures of the car interior after 10 min of warm up at -10 °C ambient temperature with focus on the driver's seat

Once the smart seat was virtually validated (thermal and also sitting comfort was evaluated) it was manufactured and assembled. Before integrating it in the vehicle it was tested under laboratory conditions in order to validate the concept. **Fig. 7** shows the surface temperature distribution of the seat in heating operation. In addition to temperatures measured in the seat, the temperature of the passenger's face was also measured. The temperature of the skin is a clear indicator to evaluate thermal sensations of humans. The metabolic system regulates the blood flow near the skin surface, the sympathetic nervous system through sweating and constriction, subcutaneous thermal structure and patterns of the facial veins [8]. The seat and the driver were heated (or cooled) as expected, proving the concept validation for the smart seat. Applying a power of 75 W to the seat enabled an air temperature reduction of 7 K in heating mode while maintaining the same comfort level for the passenger.

Fig. 7 Surface temperatures of the seat in heating operation

Impact on Energy Consumption and Driving Range

In order to quantify the impact on the energy consumption and driving range of the Fiat500e simulations of a cabin heat up for the use cases in **Table 1** were conducted. The simulations were run at 0 °C and +10 °C, which are two frequently occurring ambient temperatures during the cold season. As driving cycle the NEDC was chosen, with an average power for traction of 7 kW. During the 1180 s of the NEDC the heating power was controlled to reach the cabin target temperature at the end of the cycle. The boundary conditions for the simulated use cases are shown in **Table 2**, while radiation heating of 200 W represents two panels for both, driver and co-driver seat.

Table 1: Simulation use cases

Use Case	Air Heating Technology	Cabin Target Temperature	Seat Heating (75 W)	Radiation Heating (200 W)
1	PTC-Heater	22 °C	No	No
2	Heat Pump	22 °C	No	No
3	Heat Pump	19 °C	No	Yes
4	Heat Pump	15 °C	Yes	No
5	Heat Pump	12 °C	Yes	Yes

Table 2: Boundary conditions for the conducted simulations

Driving Cycle, Duration	NEDC, 1180 s

Ambient Temperature	0 °C and + 10 °C
Air Flow Cabin Heater	250 kg/h

Fig. 8 shows the simulation results for the average electric power for cabin heating during an NEDC at 0 °C ambient temperature. The use of the compact refrigeration unit as heat pump system (average COP of 1.50) reduces the average electric power from 3.51 to 2.34 kW (-33 %). Using seat and panel heating in addition, which enables to lower the cabin air temperature from 22 to 12 °C further decreases the average power significantly to 0.83 kW (-76 % compared to PTC heating).

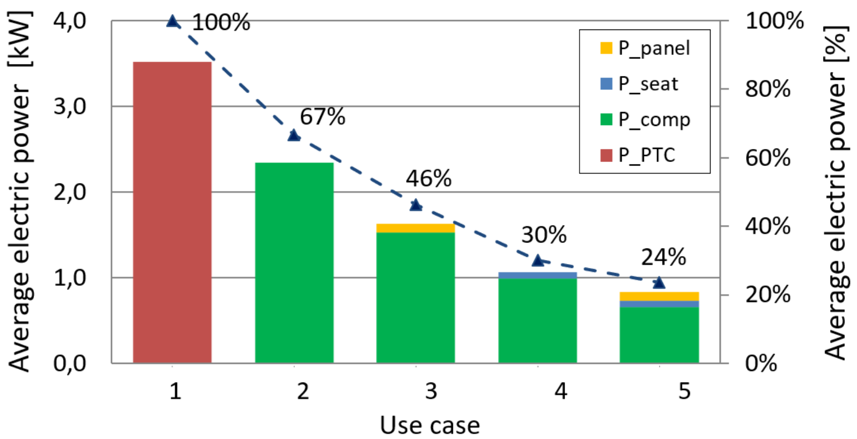

Fig. 8 Average electric power for cabin heating during an NEDC at 0 °C ambient temperature

At +10 °C ambient temperature the heat pump system enables a drastic reduction of the average power from 1.76 to 0.66 kW (-63 %) at an average COP of 2.67 (**Fig. 9**). For the use cases 3, 4 and 5 the power of the heat pump system stays the same, as the compressor is already running at minimum speed. Therefore, a further reduction of the air temperature brings only a small advantage in terms of energy consumption. Use case 4 with a cabin target air temperature of 15 °C and activated seat heating is according to the simulation results the most efficient option. The average power could be reduced from 1.76 kW to 0.43 kW (-76 % compared to PTC heating). Use case 3 (heat pump and panel heating with a cabin temperature of 19 °C) and use case 5 (heat pump with panel and seat heating) are slightly less efficient.

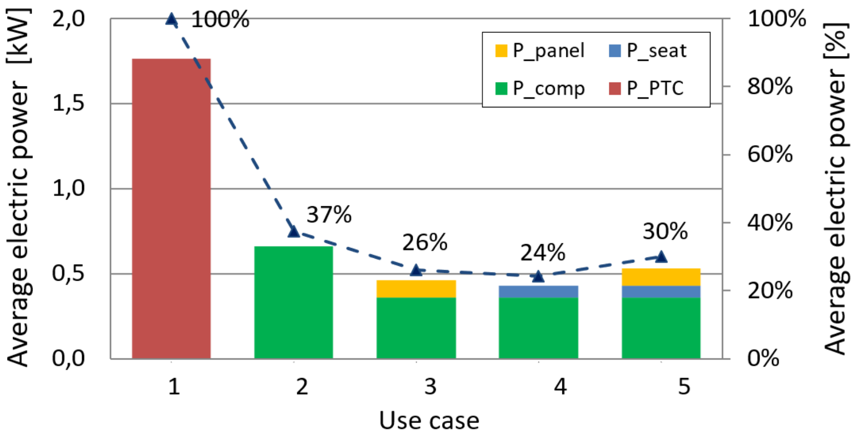

Fig. 9 Average electric power for cabin heating during an NEDC at +10 °C ambient temperature

In order to quantify the impact on driving range an average power for traction as well as for auxiliaries (pumps, fans etc.) was assumed (**Table 3**). The battery capacity of the Fiat 500e is 24.9 kWh and the average speed taken from the NEDC is 34 km/h.

Table 3: Boundary conditions for the calculation of the driving range

Battery Capacity	24.9 kWh
Average Power for Traction	7 kW
Average Power for Auxiliaries	500 W
Average Speed	34 km/h

Fig. 10 shows the simulated driving range for the Fiat 500e for the different use cases at 0 °C ambient temperature. The driving range of 77 km using a PTC heater can be improved up to 102 km (+32 %) using a heat pump combined with seat and panel heating. To sum up, the combination of different heating technologies enables to lower the cabin air temperature from 22 to 12 °C and decreases convective heat losses.

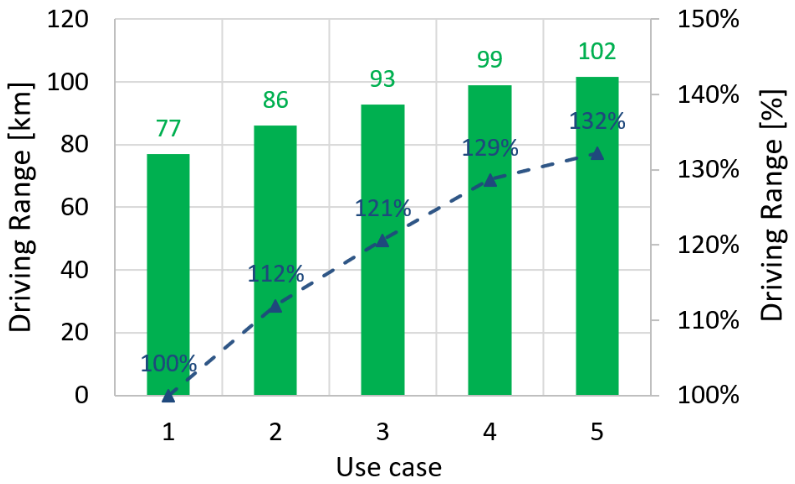

Fig. 10 Driving range for the Fiat 500e at 0 °C ambient temperature for the different use cases

At +10 °C ambient temperature the possible increase of driving range is lower than at 0 °C, as the power for cabin heating is generally lower (**Fig. 11**). Whereas PTC heating in use case 1 results in a driving range of 91 km, the heat pump system in use case 2 increases the driving range by 14 % to 104 km. Use case 4 with the heat pump system and seat heating is the most energy efficient possibility at +10°C with a resulting driving range of 107 km (+17 %).

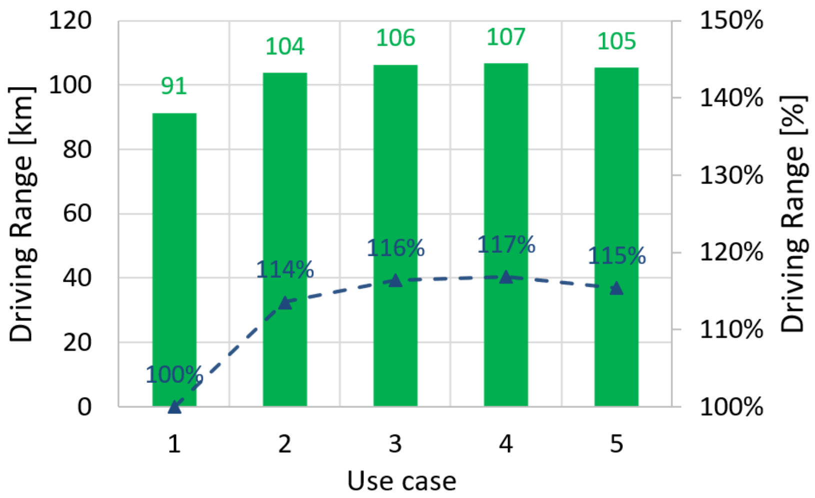

Fig. 11 Driving range for the Fiat 500e at +10 °C ambient temperature for the different use cases

Conclusions

The driving range of electric vehicles strongly decreases at low ambient temperature, especially when an electric PTC heater is used. A heat pump system is one of the most promising solutions for this problem. The closer the temperatures of the heat source (ambient air) and heat sink (passenger cabin) are, the more efficient the heat pump system is operating. A combination of a heat pump system together with seat heating and radiation heating panels enables a lower air temperature inside the cabin and improves the COP of the heat pump system at same comfort level. Further, the heat losses by warm air exiting the passenger cabin are reduced at lower cabin temperatures. The simulation results for a cabin heat up in an NEDC showed, that the heat pump system reduces the average electric power for cabin heating by 33 % (3.51 to 2.34 kW) and increases the driving range by 12 % (77 to 86 km) at 0 °C ambient temperature. A combination of the heat pump system with seat and panel heating ensuring same comfort as PTC heating, reduced the energy consumption for the heat up phase by 76 % and increases the driving range by 32 %. At +10 °C ambient temperature the average electric power for cabin heating is reduced by 63 % (1.76 to 0.66 kW) and the driving range increased by 14 % (91 to 104 km) by means of the heat pump system. Simulation results showed that the most efficient heating strategy for +10 °C is a combination of the heat pump system with seat heating including a reduction of the cabin temperature from 22 to 15 °C. This combination reduced the average electric power from 1.76 kW (PTC heating) to 0.43 kW (-76 %) and increased the driving range from 91 to 107 km (+17 %).

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List of abbreviations

COP	Coefficient of Performance
CRU	Compact Refrigeration Unit
HVAC	Heating, Ventilation and Air Conditioning
NEDC	New European Driving Cycle
PMV	Predicted Mean Vote
PPD	Predicted Persons Dissatisfied

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