Integration of Micro-CHP Units into BEVs – Influence on the Overall Efficiency, Emissions and the Electric Driving Range


Abstract—The increasing electrification of electric drive trains leads to new challenges concerning automotive system design. Since no or only a little amount of useable waste heat is available on a sufficiently high temperature level the passenger cabin heating directly influences the electric driving range for battery electric vehicles (BEVs). The scope of the paper is to analyze the integration of micro-combined heat and power (CHP) units into BEVs providing heating energy in an efficient way. Both the influence on the electric driving range as well as the overall energy efficiency in terms of primary energy and CO₂ emissions is investigated and compared to other heating systems for BEVs.

I. INTRODUCTION AND MOTIVATION

In the scope of worldwide climate discussions, politics and industry demand a drastic reduction of emissions and savings in primary energy in all energy sectors. The transport sector accounts 30 % of the overall energy consumption in Germany and plays thus an important role in this context (cf. [1], [2]). The continual growth of vehicle registrations stays in contrast to these requirements. To achieve these goals anyhow, an overall improvement of automotive systems is worth aspiring to. This concludes the optimization of all parts of individual mobility. Aside of the technical enhancements of conventional components, new fuel types, or in general, energy forms as well as new drive train concepts are considered. The electrification of the drive train is one promising approach for achieving these goals.

A disadvantage of battery electric vehicles (BEV) is the low specific energy content of current traction battery technologies which induces high vehicle weight for an acceptable electric driving range. Furthermore, the system costs for battery technologies are still expensive. Therefore, a tradeoff between user acceptance and costs has to be found.

These problems augment especially for winter conditions. The heating demand for electric vehicles may demand as much energy for heating as for propulsion for urban drive cycles. Electric drive trains are operated with high efficiency, so the amount of useable waste heat is not sufficient for covering the heating demand. Besides, the waste heat may only be provided on a temperature level below those of an internal combustion engine on a thermal stationary point. Considering the thermal masses of the cooling circuits the integration of a separate heating system is crucial.

Commonly integrated heating systems are mostly operated electrically. Apart from the direct influence on the electric driving range it should be questioned critically, if the high value energy form electricity should be used for heating purposes, regarding its overall energy conversion chain.

In the building sector combined heat and power (CHP) units offer the possibility of efficiently providing heating energy. In the last years many building systems technologies are investigated for electrified vehicles, like insulation and radiant heating or are even transferred into vehicles, like intelligent recirculation rate or heat pump systems (cf. [3]).

Thus the integration of CHP units into electric vehicles is worth considering, taking into account the overall energy efficiency, the well-to-wheel CO₂ emissions and the influence on the electric driving range.

II. STATE-OF-THE-ART HEATING SYSTEMS FOR ELECTRIFIED VEHICLES

The state of the art heating systems for BEVs are Positive Temperature Coefficient (PTC) electric heaters, heat-pump-systems or fuel-based heaters (cf. [3]).

In the following subchapters the different heating systems will be described in terms of efficiency, emissions and package.

A. Positive Temperature Coefficient (PTC) Electric Heater

There are two kinds of PTC heaters. On the one hand the heating energy is provided air-sided and the heating device is directly integrated in the heating, ventilation and air-conditioning (HVAC) system and no further heating circuit is necessary. Therefore, these systems have a fast response in heating. The additional package requirement is low, but a high voltage system is integrated near the passenger’s cabin.

On the other hand there are electric fluid heaters using a separate heating circuit. The latter one is more desirable for hybrid electric vehicles because the integration into the internal combustion engine circuit is possible.

Electric PTC heaters are self-controlling and achieve efficiencies near 100 %. But the high value energy form electricity is used for heating purposes and the electric driving range is directly influenced.

B. Heat pump systems

Other electrically operated systems are heat pump systems. They use the ambient heat which is pumped to a higher temperature level to provide heating energy. The coefficient of performance (COP) describes the efficiency of heat pump systems. It is defined by the fraction of provided
heating power $\dot{Q}$ and the electric power demand for the compressor $P$.

$$\text{COP} = \frac{\dot{Q}}{P}$$  \hspace{1cm} (1)

The COP of air-air heat pump systems strongly depends on the ambient conditions. Especially at cold winter temperatures the COP is strongly decreasing. In Figure 1 the average COP is shown as a function of the ambient temperature (cf. [4]).

![Figure 1. COP for a heat pump system as a function of the ambient temperature (cf. [4])](image)

Icing of the evaporator is a major challenge for heat pump systems especially at temperatures around 0°C – 5°C. This is caused by the humidity in the air and influences the heat exchange and thus the COP. Therefore, energy consuming deicing strategies are necessary. Solutions could be waste heat recovery system requiring complex system architectures and operational strategies (cf. [4], [5]).

The additional package requirements augment only a little since the consisting refrigerant circuit of the air-conditioning system has only to be complemented with additional valves and a condenser in the HVAC.

C. Fuel-Based Heaters

The integration of fuel based heaters has the advantage that they do not influence the electric driving range when operated since another energy form is used. These heaters are commonly used in vehicles as an engine-independent air heating systems. The efficiency is quite high and the package requirements are low. The main disadvantage of these heating systems is the integration of a separate fuel tank and the local emissions due to the combustion process (cf. [6]).

III. MICRO-CHP UNITS

Co-generation units have the advantage of both providing electric and heating energy. Thus, the overall fuel utilization rate is maximized and emissions can be reduced. An internal combustion engine, e.g. Range-Extender, works as a CHP unit but its thermal efficiency is low because only the heat in the cooling circuit is used. Exhaust gas heat exchanger may enhance the useable waste heat but in summer or at high propulsion demands overheating may occur. Besides, the thermal power, concluding the exhaust gas heat, may exceed significantly the heat demand for the passenger cabin, and the surplus of waste heat is transferred to the environment.

Due to a number of reason, among others controlling and operating times, CHP units are downsized for building systems (cf. [7]). Such so called Micro-CHP units operate with a high efficiency using the additional heat from the exhaust gas. An integration into a BEV, designed to cover the heat demand will be investigated in this paper.

The additional package is major. Aside of the engine an additional frontend heat exchanger and an exhaust gas system has to be integrated into the vehicle.

IV. METHODOLOGY

To compare the different heating systems the dynamic energy demand both for driving and heating has to be calculated by means of an integrated simulation environment. Furthermore, evaluation aspects have to be defined and applied to the results. Both methods are described in the following subchapters.

A. Integrated simulation environment

Due to the higher complexity of electrified vehicles new design tools are desirable. As mentioned before it is not expedient taking only an energetic look on the longitudinal dynamics of electrified vehicles. Aside of the growing electric energy demand for the auxiliary units, the heating demand for passengers cabin heating directly influences the electric driving range of highly electrified vehicles. For this reason a holistic vehicle simulation has been developed at the Institute for Automotive Engineering (ika), RWTH Aachen University in cooperation with the Forschungsgesellschaft Kraftfahrwesen mbH (fka) [8]. It takes into account all energetic energy flows. By this it is easily achievable to add new components or compare different architecture solutions under given evaluation aspects. The library contains different kind of vehicle models, including their drive train, passenger cabin, and their respective cooling circuits. Also building systems may be considered, to solve future challenges like vehicle-to-home (V2H) and vehicle-to-grid (V2G) applications (cf. [9], [10]). All models can be controlled and evaluated under different dynamic boundary conditions (e.g. drive cycles, ambient conditions), (cf. Figure 2).

![Figure 2. Integrated simulation approach](image)
For this paper the heating demand is determined by a passenger cabin model. It includes the different convective and radiative heat flow rates to and from the environment, as well as all enthalpy flows into and out of the cabin (cf. [11]). The nominal conditions for heating are included in the model, according to [12].

### B. Evaluation

The introduced heating systems are operated with different energy forms. In order to compare these systems, the overall energy conversion chain, over the system boundary of the vehicle, has to be taken into account. Common bases for such a well-to-wheel evaluation are on the one hand the used primary energy (PE) and on the other hand the CO₂ emissions. At first the primary energy evaluation is done.

Both the energy demand for propulsion as well as the energy demand for heating has to be considered. The primary energy demand for heating is deduced to:

\[
(PE)_{Q, HS} = \frac{Q_D}{\eta_{th, HS}} \cdot f_{p, HS}
\]

where \(Q_D\) is the heat demand, \(\eta_{th, HS}\) the thermal efficiency of the heating system and \(f_{p, HS}\) the primary energy factor (used for CHP and fuel-based heater or electricity for PTC and heat pump systems). For heat pump systems the efficiency corresponds to the COP. Similarly the primary energy demand for propulsion is calculated by the energy demand \(E_D\) multiplied by the primary energy factor of electricity \(f_{p, et}\), since the vehicle is operated purely electrically:

\[
(PE)_D = E_D \cdot f_{p, et}
\]

The overall primary energy consumption is then calculated by adding (2) and (3).

For the CHP unit an additional input has to be considered. Due to the electric energy production of the CHP, the electric demand for propulsion, supplied by the traction battery, is lowered, resulting in reduced primary energy consumption:

\[
(PE)_{D, CHP} = \left[ E_D - \left( \frac{\eta_{el, CHP}}{\eta_{th, CHP}} \cdot Q_D \right) \right] \cdot f_{p, et}
\]

Accordingly, the primary energy savings (PES) of the CHP compared to another applied heating system results in (cf. [13], [14]):

\[
PES = 1 - \frac{(PE)_{Q, CHP} + (PE)_{D, CHP}}{(PE)_{Q, HS} + (PE)_D}
\]

\[
PES = 1 - \left( \frac{Q_D}{\eta_{th, CHP}} \cdot f_{p, fuel} + \frac{Q_D}{\eta_{th, HS}} \cdot f_{p, HS} + E_D \cdot f_{p, et} \right)
\]

\[
- \left[ E_D - \left( \frac{\eta_{el, CHP}}{\eta_{th, CHP}} \cdot Q_D \right) \right] \cdot f_{p, et}
\]

The savings of CO₂ emissions is derived analogously. The primary energy factors are replaced by the specific emission factor of the corresponding energy form.

Since the electric driving range \(s_{EDR}\) is important for BEVs, it is also evaluated.

\[
s_{EDR} = \frac{E_{Batt}}{E_{D, et} + Q_{HS, et}} s_{cycle}
\]

Non-electric heating systems do not influence the electric driving range and thus are not considered in (7). When the CHP unit is operated, the generated electricity directly reduces the energy demand for propulsion, so \(E_{D, et}\) is reduced accordingly to (4) but without taking into account \(f_{p, et}\).

In the subsequent chapter simulation results are presented using the introduced method to evaluate the heating systems.

### V. NUMERICAL RESULTS

#### A. Simulation Setup and boundary conditions

For this paper a battery electric vehicle (BEV) is considered. The vehicle data for the longitudinal simulations are listed in TABLE I. All components (gears, electric machine and electric converter) are modeled with a fixed efficiency resulting in an overall drive train efficiency. The traction battery has a useable energy content of 19 kWh.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Vehicle mass</th>
<th>1490 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cu-value</td>
<td>0.33</td>
</tr>
<tr>
<td>Cross-section area</td>
<td></td>
<td>2.14 m²</td>
</tr>
<tr>
<td>Rolling resistance coefficient</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Cabin volume</td>
<td></td>
<td>3 m³</td>
</tr>
<tr>
<td>Window surface</td>
<td></td>
<td>2 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drive Train</th>
<th>Drive train efficiency (NEDC)</th>
<th>(\eta = 0.85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Content Battery</td>
<td></td>
<td>19 kWh</td>
</tr>
</tbody>
</table>

TABLE II shows the technical data of the considered heating systems and a CHP unit similar to [16]. The power of the CHP unit may be reduced, operating in a modulated way, down to 40%. The resulting lower efficiency is taken into account by reducing the electric efficiency at modulated operation. The PTC heater and the fuel based heater are assumed with efficiencies of 100% respectively optimistic future 90%. The average COP of the heat pump system is assumed as a function of the ambient temperature according to Figure 1.

The additional masses for the single heating systems are considered in the simulations. The weight of the CHP unit is based on the weight of a Range-Extender supplemented by the masses for heat exchangers and cooling circuit. For the other heating system the additional masses are neglected.
### TABLE II. DATA OF HEATING SYSTEMS

<table>
<thead>
<tr>
<th>State-of-the-art heating systems</th>
<th>PTC heater</th>
<th>η = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pump system</td>
<td>COP = cf. Figure 1</td>
<td></td>
</tr>
<tr>
<td>Fuel-based-heater</td>
<td>η = 0.9</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHP unit</th>
<th>Thermal power</th>
<th>Q = 5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power</td>
<td>P = 2.7 kW</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>ηel, CHP, min = 0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ηel, CHP, max = 0.55</td>
<td></td>
</tr>
<tr>
<td>Fuel utilization rate</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Additional fuel weight</td>
<td>100 kg</td>
<td></td>
</tr>
</tbody>
</table>

The simulations are carried out for the New European Drive Cycle (NEDC) and for different ambient conditions (cf. TABLE III).

### TABLE III. BOUNDARY CONDITIONS

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>NEDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>s=11 km, t=1180 s, v0=33.6 km/h</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ambient temperatures T</th>
<th>-20°C...+15°C</th>
</tr>
</thead>
</table>

| Solar radiation f(T), cf. [16] |

Two different fuel types are considered for the CHP unit. On the one hand commonly used diesel fuel and on the other hand compressed natural gas (CNG). The fuel based heater is assumed to be operated by diesel fuel. Both the PTC heater and the heat pump system are operated purely electrically. For the following well-to-wheel analysis the corresponding primary energy factors and the specific CO₂ emissions for the different energy forms according to [18] and [19] (electricity) are used and listed in TABLE IV.

### TABLE IV. SPECIFIC CO₂ EMISSIONS ACCORDING TO [18], [19]

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Primary energy factors</th>
<th>Specific CO₂ Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>1.22</td>
<td>302 g/kWh</td>
</tr>
<tr>
<td>CNG</td>
<td>1.12</td>
<td>238 g/kWh</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.68</td>
<td>565 g/kWh</td>
</tr>
</tbody>
</table>

### B. Evaluation of primary energy demand

The following plots show the results for the used primary energy for the different heating systems. Figure 3 illustrates the primary energy demand for the above mentioned heating systems for ambient conditions, starting from -20°C to 15°C. Since in this evaluation only the heating demand is taken into account, the electricity credit method is used for the CHP unit (cf. [7]). This means, that the benefit of generating electricity multiplied with the primary energy factor for electricity is subtracted from the primary energy demand.

For cold ambient temperatures up to -10°C both the fuel-based heating system and the CHP units have a lower demand. Starting from there the heat pump system is more efficient than the fuel-based and for temperatures above 5°C even than the considered CHP units. This is caused by the increasing COP of the heat pump system at higher ambient temperatures (cf. Figure 1) and as mentioned above, the assumed CHP unit may only be modulated down to 40% of its nominal power. Thus, for ambient temperatures above 5°C, the consumed fuel rate stays the same. This leads to a lower efficiency of the CHP unit because only part of the provided heat energy can be used for cabin heating. The surplus of heat is transferred to the environment by a heat exchanger. By this, the overall fuel utilization rate is decreased and the fuel-based heater is even better than the CHP units at 15°C. A possibility to enhance the efficiency is the integration of a thermal storage, e.g. operating with sensible or latent material, so the surplus of waste heat may be recovered. At all temperature levels the electric PTC heater has the highest primary energy demand.

In Figure 4 the primary energy demand for both propulsion and heating is shown for the different systems. According to (4) the electric energy demand for driving is set
in contrast to the produced electric energy of the CHP unit. The higher energy requirement for propulsion due to the higher weight of the CHP unit is included in the results. Anyhow it does not change the overall tendency. The results show the decreasing influence of the heating energy compared to the energy demand for propulsion.

Disadvantageous of a primary energy evaluation is that the influence on the environment in terms of CO\textsubscript{2} emissions is not covered, as the specific emissions of the single energy forms are not taken into account. This is done in the next subchapter.

C. Evaluation of CO\textsubscript{2} emissions

In Figure 5 the results for well-to-wheel CO\textsubscript{2} emissions for the different heating systems are shown. A slightly different picture is stated out in the results. The heat pump system has lower emissions than the fuel-based heating system, starting from -10°C and from -5°C even than the diesel operated CHP unit. Since the CHP unit may only be modulated down to 40 %, the fuel utilization rate is low without using a thermal storage and thus even the electric heater has lower emissions that the diesel operated CHP unit at 15°C.

This is reasoned by the relation between the specific CO\textsubscript{2} emissions of the different fuel types and the specific emissions for the electricity mix (cf. TABLE IV). Especially the fraction between the higher carbon fuel diesel to the electricity mix is about 17 % higher than the fraction of the respective primary energy factors (cf. TABLE IV). Due to that, the electric heating systems, especially the heat pump system, improves in the comparison. Since the fractions of the low carbon fuel type CNG to electricity is similar to the respective primary energy fraction, the tendancy of the results for CNG do not shift compared to the primary energy demand results. A clear benefit can be stated out for the CNG operated CHP unit for temperatures below 5°C, regarding the well-to-wheel CO\textsubscript{2} emissions for heating purposes.

In figure 6 the overall CO\textsubscript{2} emissions, both for propulsion and for heating, are presented.

Apart from the emissions, especially for customer acceptance of electrified vehicles, the influence of the different heating system on the electric driving range has to be considered.

D. Evaluation of electric driving range

The simulated electric driving range is calculated according to (7). For the fuel-based heater no further electric energy has to be provided for heating purposes so the driving range corresponds to the energy demand for propulsion. Both electric heating systems have major limitation, especially at cold temperatures. Due to its electric power generation a clear benefit is stated out for the CHP unit for all ambient temperatures. The electric driving range is improved more than twice when the CHP unit is operated in a non modulated way (cf. Figure 7).

In Figure 8 the influence of heating on the electric driving range is shown on a percentage scale. All values are compared to the electric driving range for propulsion purposes only.
As stated in the introduction the limitations for both electric heating systems are crucial, resulting in a reduction of up to 50 % for the PTC heater, respectively 45 % for the heat pump system. The high benefit of more than 100 % for the CHP unit is explained by the low propulsion energy demand of the considered driving cycle NEDC. Subsequently, the respective percentages, benefit and loss, decrease for a more energy consuming cycle.

VI. CONCLUSION AND OUTLOOK

In this paper the integration of a Micro-CHP unit into BEVs is investigated and evaluated by means of an integrated simulation environment in terms of overall primary energy consumption, CO₂ emissions and electric driving range. The results show clear benefits on primary energy consumption, especially for strong winter scenarios. Concerning the CO₂ emissions, a low carbon fuel-type is favorable for the CHP unit. Apart from the energetic point of view, the electric driving range can be enhanced up to twice its value for the assumed drive cycle. On the other hand the vehicle demands a higher package and is not operated as a zero emissions vehicle when heating energy is required.

The integration offers additional opportunities. For example synergetic effects between transport and building sector are a promising possibility to reduce the overall energy consumption thus the CO₂ emissions. Such an approach is currently being investigated at the ika [9], [10].

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