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Heating an electric car with a biofuel-operated heater during cold seasons: design, application, and testing

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ABSTRACT
The automotive industry is currently undergoing far-reaching structural changes. Automobile manufacturers are pursuing intensive scientific research and technological development in the field of alternative drive systems, such as electric powertrains. If electric car batteries are charged with regenerative generated electricity, their emission output is zero (from a well-to-wheel view). Furthermore, electric drives have very high efficiency. At cold temperatures, however, the battery power drops due to energy-intensive loads, such as the heating of the passenger compartment, and this consequently reduces the range dramatically. Therefore, the focus of this research work is external energy supply for the required heat capacity. The auxiliary energy may be generated by renewable energy technologies in order to further improve the CO_2 balance of electric vehicles. The paper deals with the design, application, and testing of a biofuel-operated heater to heat the passenger compartment of a battery-powered electric car (a Renault ZOE R240). The practical use of the heating system is analyzed in several test drives, performed during winter 2018. The results as well as the range extension of the electric car that can be achieved by substituting the on-board heating system by the fuel-operated heater are quantified herein.

Section: RESEARCH PAPER

Keywords: electric vehicle; range extension; air-conditioning; fuel-operated heater; biofuel; prototype

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1. INTRODUCTION

Battery-powered electric vehicles (BEV) offer great advantages over conventional combustion engine-driven cars. However, due to the limited charging possibilities and insufficient range during winter months, there are still some serious limits to widespread electro-mobility.

Various studies indicate that the power of such a battery and thus the range of the vehicle are affected by the heating of the passenger compartment during winter [1-4]. Figure 1 details the driving ranges of the research vehicle (Renault ZOE R240, see Figure 5) experienced in different driving scenarios (i.e., under varying ambient temperatures).

According to the New European Driving Cycle (NEDC), the range of a Renault ZOE R240 equipped with a 22 kWh battery should be about 240 km. The NEDC is intended to map typical driving cycles for vehicles and consists of four urban trips and an extra suburban driving cycle [5]. Figure 1 clearly shows that the realistic ranges are obviously different from the NEDC.

In optimal conditions, at an ambient temperature of 20 °C in ECO mode (maximum velocity 94 km/h, no heating and cooling of the passenger compartment), a maximum range of 170 km can be achieved. Our experience is that the vehicle has an average range of 120 km in summer (hot days, with air conditioning operational) and 80 km in winter (cold days, with the on-board heating system operational).

The high-range losses can be explained by the operation of the energy-intensive on-board heating and cooling systems. Furthermore, the impact on the driving range is even higher at cold temperatures, since the battery capacity decreases rapidly at lower temperatures below 0 °C. According to [7], heating significantly reduces the range of a Mitsubishi i-MiEV. This clearly indicates a high demand for further research aiming to advance electro-mobility.

The aim of our research is therefore to test the design and application of a fuel-operated heater in BEVs and to quantify the range increase that can be achieved by means of battery relief.

2. STATE OF THE ART

2.1. Current state of the art on air-conditioning electric vehicles

The heating of the passenger compartment of electric vehicles that are currently available is mainly carried out by commercial air-conditioning systems as in combustion vehicles. Due to insufficient heat losses of the battery compared to internal combustion engines, these air-conditioning systems require a great deal of energy in winter, which is taken from the battery. Since the generation of heat is easier to handle than that of cold and the maximum energy savings possible can be achieved in winter, most of the research work focuses on providing heat for the vehicle's passenger compartment. Currently, three heating concepts are in use for BEVs:

1. Electrical high-voltage air heaters
2. Electrical high-voltage water heaters
3. Heat pump heaters

Electrical high-voltage heaters are a specific type of electric heaters that are powered by battery energy. They can be applied in both air- and water-cooled vehicle systems. High-voltage water heaters allow for energy efficient usage but reduce the driving range by up to 40 % [8]. Heat pump heaters have remarkably high energy efficiency, but still need electric power for operation. This advanced technology can provide heating as well as cooling for the electric vehicle [9].

The Renault ZOE R240 is equipped with a heat pump system for heating and cooling. The disadvantage of the abovementioned heating systems is that the required electrical energy for their operation is drawn from the vehicle battery and thus considerably reduces the driving range of the battery-powered electric vehicle. Therefore, providing a secondary source of energy is a promising area of research. Heat energy from regenerative sources can take on the task of heating. Furthermore, the electrical energy provided may also power alternative air-conditioning systems. Various studies indicate that the use of regenerative energy for air conditioning in closed rooms is most promising [10-11].

2.2. Alternative technologies for air-conditioning electric vehicles

This section gives a comprehensive overview of the most promising regenerative technologies for heat and electricity generation. These four technologies are shown in Figure 2.

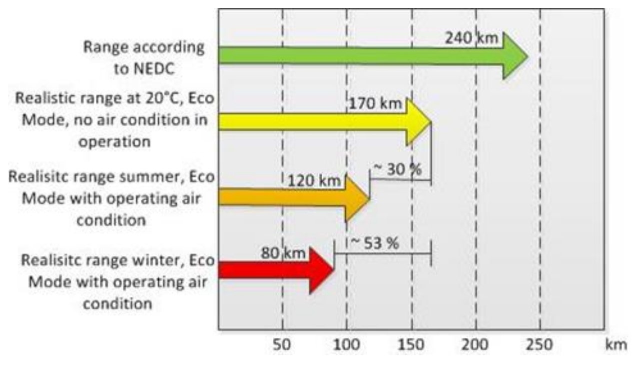

Figure 1. The range of Renault ZOE R240 according to [6].

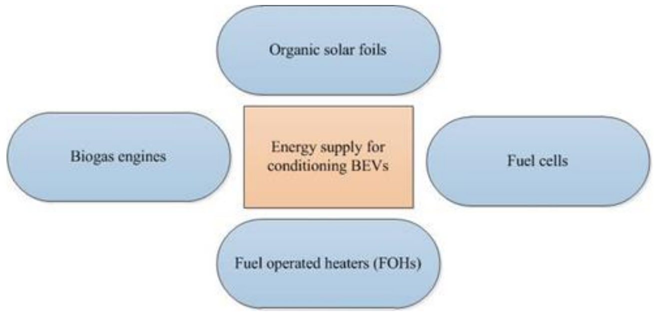

Figure 2. An alternative energy supply for auxiliary systems in BEVs.

Several studies (such as [11]) show that there is a huge range of applications for biogas engines in electric and hybrid vehicles. Furthermore, Jaguar and Bladon Jets developed a range-extended battery-powered electric vehicle that is supplied with electricity through two small biogas engines [12]. This application seems useful if a small size, a light weight, and high output delivery is significant. Another research area is the use of fuel cells to generate energy and heat. Fuel cells generate about 40 % waste heat, which can be used for cabin heating purposes [13]. The production of hydrogen (which is necessary for the fuel cell operation) is still very expensive and energy intensive. Hydrogen is mainly produced in pilot plants and is thus unavailable in a sufficient amount.

Webasto manufactures solar sunroofs for cars that provide additional electric energy for air conditioning the passenger compartment. Latest studies focus on the usage of so-called organic solar foils since no rare earths are needed. Organic solar foils can be easily implemented on car roofs and, if translucent, also on windows. The generated electric power can operate several fans, which lead to a continuously fresh air supply and help to cool down the passenger compartment. Furthermore, these solar foils help to reduce the direct radiation on the car. The implementation on the car is relatively easy: The foils are glued on the rooftop or windows, and the necessary cable connections can be executed on the inside of the vehicle [14].

Auxiliary heaters using biofuels are another promising approach. This technology can support or substitute the air conditioning of BEVs. Because the heat production is mostly independent, the use of fuel-operated heaters (FOHs) does not have a strong impact on the battery. Heat is directly generated by burning fuel. For the most part, FOHs can be implemented directly into the air-conditioning system of the vehicle. There are two possibilities for FOHs: water and air heaters. The installation of FOHs into the engine compartment, the passenger compartment, or at the exterior of the vehicle is quite easy. Figure 3 and Figure 4 show the main structure of air-conditioning circuits, including FOHs.

The study of Mimuro et al. [4] shows that FOHs are a workable solution to the range difficulty. Several manufacturers are working on FOHs for electrified cars. Eberspächer has already implemented an FOH prototype in the Mitsubishi i-MiEV. They even manufacture an FOH (Monofuel Hydronic-E-Mobility E4S, based on ethanol E100) that leads to emission-free operation [15]. It is obvious that biofuels would be a sensible source of energy for running FOHs.

Kohle et al. [16] point out that the energy savings that can be achieved by using an ethanol FOH instead of an electrical heater is up to 30 %. Therefore, a BEV was tested according to the TÜV SÜD Electric Car Cycle (TSECC), which defines the velocity profile as a combination of three street types [17], at an ambient temperature of -7 °C. The applied fuel heater was a

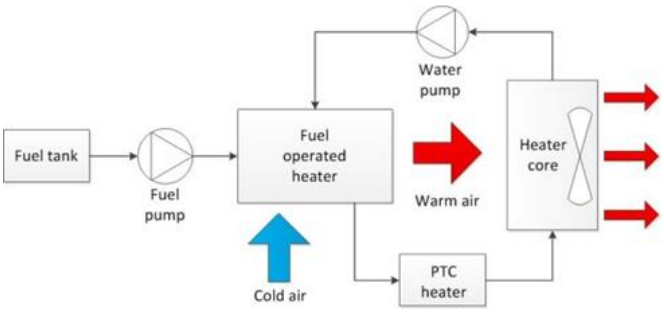

Figure 3. A water circuit incorporating a fuel-operated heater.

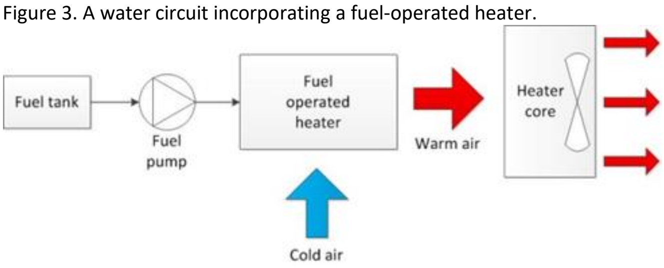

Figure 4. An air circuit incorporating a fuel-operated heater.

Hydronic-E-Mobility E4S heater, which uses 100 % ethanol (E100) to operate. The range benefit was calculated according to the energy consumption.

Due to the uncomplicated production and widespread availability of bioethanol as well the easy implementation of the heater and the auxiliary systems in the vehicle, bioethanol FOHs seem to offer a good contribution to the heating systems of the future [18].

Apart from research on alternative energy concepts, several researchers deal with new concepts concerning air conditioning in general. Decentralized air conditioning allows each passenger to individually control their surrounding temperature. This could lead to greater energy savings and thus relieve the strain on the vehicle battery. The most promising approaches are explained below.

Area heaters, such as resistance heating foils, can heat up cold areas around the passenger, which will lead to a higher level of comfort for the passengers due to the surface radiation instead of direct hot air streams. The required electricity can be generated by solar cells, mounted on the vehicle's exterior. Ackermann et al. [19] evidence that area heaters should be mounted close to the body to achieve perfect heat distribution to the body. Their study shows how area heaters contribute to the comfort of the passenger and an energy efficient Heating, Ventilation, and Air Conditioning (HVAC) system.

Layer heaters, a further development of common high-voltage heaters, are already in use in different industrial applications. When supplied with electrical power, they emit heat. The work of Cap et al. [20] points out that the efficiency of these layer heaters can be up to 99 %.

Generated sun power can support continuous ventilation in the compartment, which leads to a continuously fresh air supply and lowered heating in the car cabin. The required energy can be produced by solar foils that are mounted on the car roof.

Adsorption cooling shows potential for efficient use in electric vehicles. It is not yet commonly used due to a few of its limitations, such as the low capacity of the most currently used adsorbents. Abdullah et al. [21] point out that adsorption cooling will be common if further improvements are achieved. However, the problem concerning automotive applications is the missing systems in the required performance class.

3. RESEARCH QUESTIONS

As mentioned above, the implementation of a bioethanol-operated heater seems to be a good contribution to the heating system of a BEV. Thus, two questions arise:

1. Can a bioethanol-operated heater contribute to sufficient heating of the vehicle's passenger compartment from a technical and legal point of view?
2. How large is the range increase achievable by means of battery relief?

To answer these questions, an FOH is implemented in the Renault ZOE. Due to legal constraints, diesel is currently used instead of bioethanol in order to receive permission to use the vehicle on the roads in Germany.

The heater is hoped to contribute to sufficient heating of the vehicle's passenger compartment. Some modifications to the vehicle are necessary. From a legal point of view, the implementation is subject to conditions, but possible. However, only individual approval is possible in the current legal situation. A series approval is not achievable, especially when using bioethanol as the vehicle's fuel. The necessary steps for the technical realization and first results on the range increase are presented and discussed in the following sections.

4. RESEARCH VEHILCE: RENAULT ZOE R240

For practical testing and research purposes, the University of Applied Sciences Ansbach has a battery-powered Renault ZOE R240 [6] at its disposal (Figure 5). Table 1 details the relevant technical data of the Renault ZOE R240 research vehicle.

Figure 5. Research vehicle Renault ZOE R240.

Table 1. Technical data of the Renault ZOE R240 (assembled in 2015) [22].

Technical data	Renault ZOE R240
Electric motor	Three-phase synchronous generator
Cooling system	Air-cooled
Battery	22 kW
NEDC range	240 km
Power	65 kW (88 HP) peak
Max. torque	220 Nm
Max. speed	135 km/h
Consumption	13.3 kWh/100 km

Figure 6. The assembled fuel-operated heater (1), air tubes (2), enclosed fuel tank (3), and fresh air intake (4) in the luggage compartment.

5. INSTALLATION AND APPLICATION OF THE FUEL-OPERATED HEATING SYSTEM

The main component of the FOH implementation is a fuel-operated auxiliary air heater from Eberspächer (Airtronic D2) with a maximum power output of 2.2 kW. The conversion measures performed at the vehicle are described herein. The auxiliary heater and corresponding peripherals (fuel tank, etc.) are mounted in the vehicle's luggage compartment (Figure 6 and Figure 10) or below the floor panel of the vehicle (Figure 7).

The heated air is guided to the front of the passenger compartment using insulated tubes with an inner diameter of 60 mm. This diameter keeps the back pressure and thus the noise level of the built-in fan low. The tubes are routed underneath the backseat and the corresponding interior trim of the vehicle (2, Figure 6) and end in the front-facing diffusors behind each front seat (Figure 9). To avoid unpleasant dry air in the passenger compartment, the air intake (4, Figure 6) provides fresh air from outside the vehicle into the passenger compartment. The air intake as well as the exhaust for the fuel-burning process are located underneath the vehicle to completely separate these streams from the inside of the vehicle. To keep the impact on the environment as low as possible, the combustion air and the exhaust gases are guided through appropriate silencers. The exhaust gases are additionally cleaned in an oxidizing catalytic converter, which is mounted (similarly to the fuel pump) close to the heater's fuel supply underneath the floor panel of the luggage compartment (Figure 7).

Figure 7. Partly mounted silencer (1) and oxidizing catalytic converter (2) for exhaust gases (view from below the floor panel).

Figure 8. "EasyStart Timer" (1) mounted next to the steering column.

Figure 9. Front-facing hot air diffusor (1) on the right side of the backseat (2).

The auxiliary heater and the fuel system are controlled with the "EasyStart Timer" control unit of Eberspächer. The control unit is mounted next to the steering wheel to allow complete control of the auxiliary heater while driving (Figure 8).

To regulate the power of the auxiliary heater automatically, a temperature sensor is mounted at the dashboard next to the vehicle's air vents. This sensor-controlled heating protects the passengers from excessive heat and reduces the fuel consumption of the heater. To satisfy legal regulations and to keep the vehicle road legal in Germany, an additional ventilated enclosure is fitted to the fuel tank in the luggage compartment (3, Figure 6). A bioethanol-powered heater requires more action to keep the vehicle permanently road legal.

Figure 10. Fuel tank (1, without enclosure) as well as wiring and piping (2, not covered by interior trim) during installation and assembly.

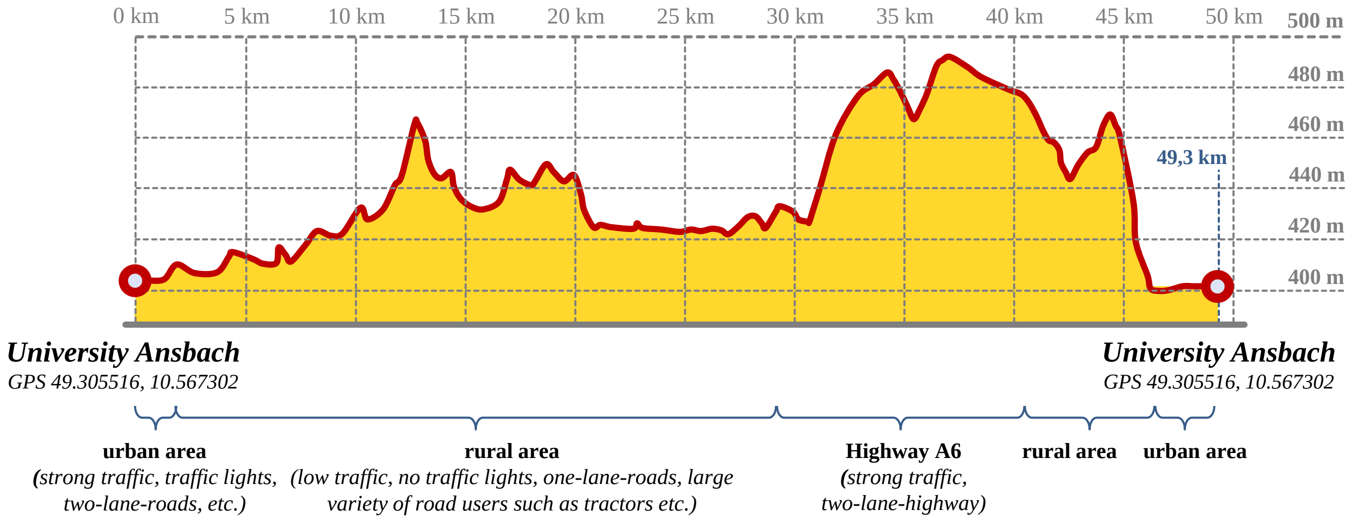

Figure 11. Elevation profile of the test route.

6. EXPERIMENTAL PROCEDURE AND TEST RESULTS

The results from the first test drives with different driving modes and heater settings in the vehicle are presented and discussed in this section.

In advance of the test drives, a test route of 49.3 km was defined in order to keep the energy consumption comparable. The test route is a combination of city and country roads as well as a short highway section. This combination ensures that every traffic and load scenario is included in the test drives. The elevation profile (Figure 11) of the test route is diversified but with more flat and uphill sections than downhill sections for recuperation. The overall altitude difference is 92.6 m (maximum 491.4 m, minimum 398.8 m). The selected roads are main roads, but with a lower traffic volume than other roads in the area around Ansbach. The section through the city is routed in such a way that good progress is guaranteed, even during rush hour. The driving data was recorded using the CAN-Bus by means of the vehicle's onboard diagnosis interface (OBDII) with the open-source application CanZE [23].

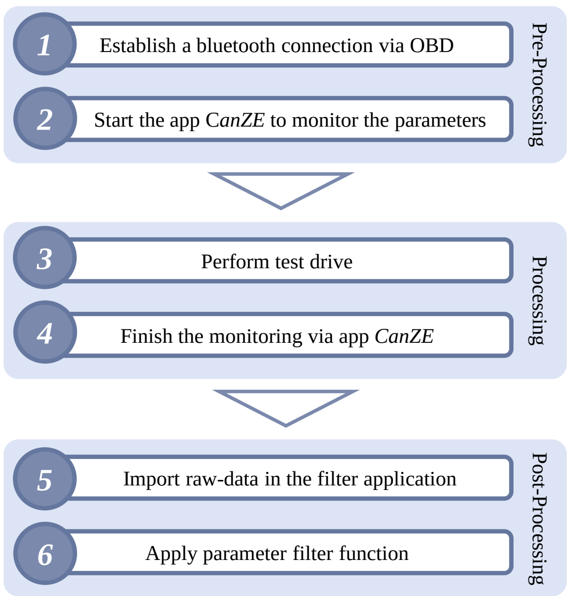

Figure 12. Procedure for acquiring structured driving data [24].

The procedure for acquiring the data of the relevant driving parameters has three main steps: pre-processing, processing, and post-processing (Figure 12).
During the pre-processing, it was necessary to establish an adequate Bluetooth connection between the car's OBDII and a device that provides access to the CanZE application (in this case, an Android tablet). The processing step includes the test drive as well as the entire monitoring activities of the driving data. The application CanZE receives information about driving parameters. However, the application stores those in an unstructured matter in raw files (such as *.field). By closing the app, the monitoring process (as well as the storage of the gained data in the raw files) was completed.

To provide an adequate database for the further analysis and visualization of driving parameters, a filter application is applied during the post-processing phase. This application extracts the corresponding information about a driving parameter in a structured manner by sorting the raw data in accordance with the given parameter IDs and time stamps. These parameter IDs were previously defined by the car manufacturer's on-board protocol and are not subject to change [24].

Two test drives, one at -11 °C and one at -13 °C, are taken as examples in Figure 13. Both test drives were conducted between 8:00 a.m. and 9:00 a.m. on two consecutive days. The test drive at -11 °C was conducted under the defined standard test conditions (STCs). The STCs include the driving mode of the vehicle set to Economy (ECO) with a limited top speed of about 94 km/h, the vehicle's heater set to 22 °C with fresh air intake from outside the vehicle, and the blower set at level 2. The vehicle's battery was fully charged before the test drive was conducted. The settings for the compared test drive at -13 °C are the same, apart from the use of the auxiliary heater instead of the vehicle's heater. The uneven records of CanZE caused the different time intervals displayed in Figure 13 and Figure 14. The record intervals range from four to seven seconds and are not evened out for the graphs.

A comparison of the graphs in Figure 13 shows that the battery's State of Charge (SOC) without the auxiliary heater drops with a larger gradient and earlier than the SOC with the auxiliary heater switched on. The substitution of the vehicle's heater results in a SOC difference of 0.08 after the test drive. This is equivalent to a range increase of about 21.6 %. The difference in SOC at the beginning is caused by the batteries' behaviour at

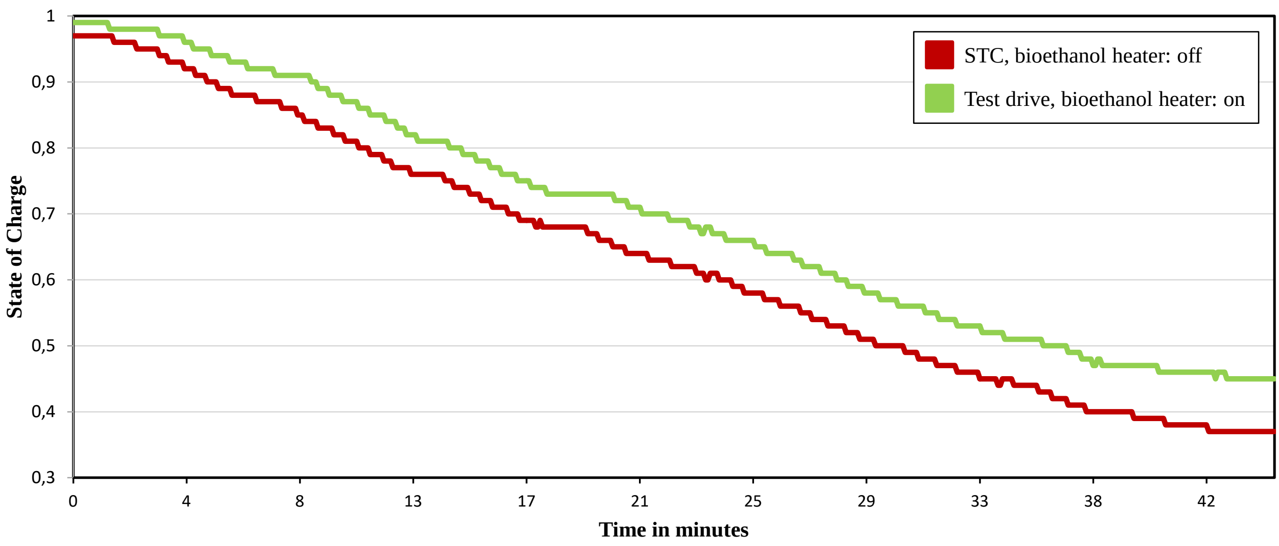

Figure 13. State of charge of two test drives at -11 °C (STC) and -13 °C (test drive); (SOC = 1: fully charged battery; SOC = 0: entirely uncharged battery).

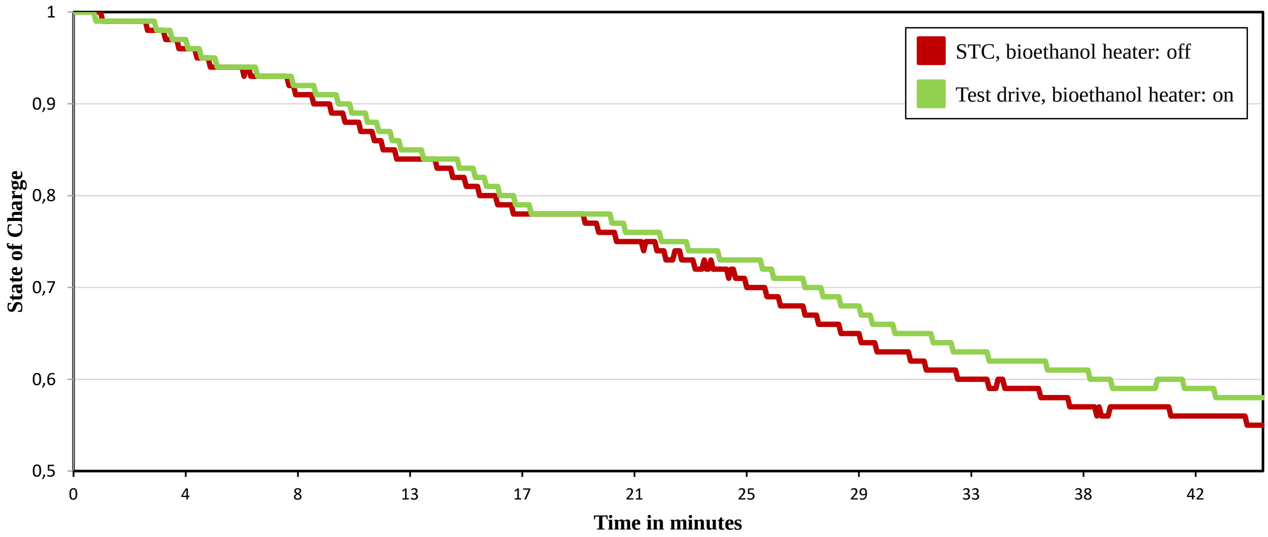

Figure 14. Comparison of the state of charge in two test drives at 1 °C; (SOC = 1: fully charged battery; SOC = 0: entirely uncharged battery).

cold temperatures, which in some instances prevented the SOC from reaching 100 %.

A comparison of the graphs in Figure 14 delivers a very similar result as the graphs in Figure 13. The gradient of both curves is lower than the gradient for colder conditions.This gradient difference is caused by the lower battery capacity in cold conditions as described in section I. The difference in SOC caused by the auxiliary heater is 0.03. This means a calculated range increase of about 5.5 %.

A comparison of the curves in Figure 13 and Figure 14 with the elevation profile in Figure 11 shows that the gradient difference between the curves in both figures is solely due to whether the vehicle's heater switched on or off. The different heater settings can be clearly identified in both figures.

7. CONCLUSION

The gained results clearly show that the impact of the vehicle's heating unit on the achievable range during winter or cold conditions is significant and measurable. Although the potential range increase observed during the first test drive is already at an acceptable level, the expected energy consumption in even colder climates (countries with ambient temperatures below -20 °C during cold seasons) is significantly higher than in the mild central European climate.

The potential range increase between 5.5 % and 21.6 % (without any further optimization of the vehicle or the auxiliary heater) shows that the concept of substituting the vehicle's heater is a promising possibility for increasing the range of BEVs in todays' state of technology. We intend to carry out further tests with the research vehicle on an air-conditioned chassis dynamometer to verify the obtained results from the test drives on the road. The chassis dynamometer allows a more exact driving performance and thus a more precise view of the heater's impact on the vehicle's range. Furthermore, the air conditioning of the chassis dynamometer is capable of providing test scenarios with ambient temperatures as low as -35 °C. This allows an appraisal of the impact on BEVs in colder countries such as Norway, Finland, or Sweden.

However, the proposed method does have several limitations. The data acquisition procedure is not fully automated and thus not yet able to provide real-time data. Furthermore, the statistical reliability of the data (and the on-board computer system) is currently insufficient. A promising approach may be the implementation of artificial intelligence (such as artificial neural networks [25]) for a more realistic estimation of the remaining driving range. Finally, to increase comparability between several test scenarios (according to an adequate experiment design), the development and application of a numerical test drive simulation [26] is recommended.

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