Approach to Modeling Energy Consumption of Auxiliary Consumers in Electric Vehicles

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***Abstract*—To fully use the benefits of a hybrid energy storage system in an Electric Vehicle (EV), it requires an effective energy management system to control the energy flow. Knowledge of how energy consumption is generated in EVs is, therefore, important for the development of such a system. Since one of the biggest energy consumptions in modern EVs are generated by the auxiliary consumers, an auxiliary model needs to consider all relevant auxiliary consumers, including the heating/air-conditioning system and other switched, dynamic, comfort and continuous consumers. The vehicle interior is, therefore, modeled using a 1-zone air model and the auxiliary consumers (such as heating/air conditioning, power steering and others) are adjusted based on environmental conditions. The electric power steering's energy demand is calculated dynamically during the journey. The energy consumption of the heating system matches literature data with deviation less than 8%, while the consumption of other auxiliary consumers matches measured values with deviation of 2.8%. The focus is on the energy consumption of auxiliary consumers in EVs, which are a significant factor in the energy flows of the vehicle. The model accounts for factors, such as weather and driving behavior, that affect the use of auxiliary consumers and the resulting energy consumption.**

Keywords-Electric Vehicle (EV); Auxiliary Consumers; Heating, Ventilation, Air Conditioning (HVAC); Energy Consumption; Simulation Based; Weather.

I. INTRODUCTION

The utilization of Hybrid Energy Storage Systems (HESS) in electric vehicles has been the subject of growing interest in recent years, as it offers a unique combination of the benefits of both lithium-ion batteries and supercapacitors. The integration of these two energy storage technologies results in a system that boasts both high energy density and high-power density. The effective management of energy flow between these two storage technologies requires the implementation of an intelligent Energy Management System (EMS) [12]. For the development and testing of such systems, it is necessary to model the energy flows in the vehicle as realistically as possible. Based on these models, the EMS can make a prediction of the expected range and suggest and/or take appropriate corrective steps if any action is required [12]. Alongside the powertrain, the auxiliary consumers are the second-largest energy consumers in an electric vehicle. Heating and air conditioning of the interior in particular consume a lot of energy [11]. Since electric vehicles have to operate with a limited energy capacity or comparatively long charging times, an accurate representation of the energy flows and the respective energy consumption is significant for model-based development approaches of management systems like the EMS presented in [12]. The use of auxiliary consumers in a vehicle depends on many different influencing factors. For example, the vehicle's lights depend on the weather, the time of day, the season, and the route. The use of the radio and the heating/air conditioning system is in return dependent on the driver. So, the presented model has to simulate the usage of the auxiliary consumers and the resulting energy consumption realistically, while at the same time taking external influences such as weather and route conditions into account.

Section 2 presents an investigation about the state of the art and gives an overview about modelling of auxiliary consumers in EVs. In Section 3, the individual models (vehicle cabin, Heating, Ventilation, Air Conditioning (HVAC) system, and other auxiliary consumers) are presented. Section 4 presents the individual validations of the used model in this project. Afterwards, Section 4 discusses and concludes the results of this work.

II. STATE OF THE ART

The paper of Basler [1], Baumgart [2], Konz et. al. [10], Kruppok [11] and Suchaneck [16] are studied to compare with the modeling approach of this investigation. The research focuses on modeling the HVAC system, as it is the main auxiliary consumer of an electric vehicle. Modelling the other auxiliary consumers via a constant power is sufficient since the transient behavior is not the focus, only their energy consumption. However, the additional consumers must be modeled dynamically based on ambient and route conditions for a realistic estimation of energy flows. Route-specific data is required and can be obtained from suitable sources or entered manually.

This work's focus is on energy flow calculations and does not aim to calculate additional range reductions of an electric vehicle or model comfort behavior. Instead, it aims to realistically calculate energy consumption through a realistic integration of route and environmental parameters into the auxiliary consumer model.

III. MODEL ENVIRONMENT

The model is generated in C-Code which is integrated into the simulation tool CarMaker. On one side through the interface, it is possible to set options and starting conditions for the model. On the other side, it is possible to return the calculated energy flows to the CarMaker environment for further processing [9]. While the transient behavior of the HVAC system determines the energy consumption significantly, the transient behavior of the other consumer (e.g., lightning, wipers) is not relevant for an accurate energy flow calculation. That's why the model is split into the blocks of HVAC and other consumers. The other consumers can be modelled as consumers with constant power demand when turned on.

A. *Heat Flow Balance of the vehicle cabin*

The vehicle's exterior surfaces are in heat exchange with the environment. Solar radiation passes directly through the glazed surfaces of the vehicle into the passenger compartment ($\dot{Q}_{trans}$) and the exterior surfaces of the body heat up. At low ambient temperatures, the heated body parts release their heat ($\dot{Q}_{body}$). A heat flow is supplied by the HVAC module ($\dot{Q}_{HV\,AC}$). Since the principle of mass conservation applies within the vehicle interior, the air mass flow supplied by the air-conditioning system must be able to escape again from the vehicle, as otherwise there would be an increase in pressure in the cabin, which is not the case (for real vehicles). The calculation of the dissipated heat flows $\dot{Q}_{loss}$ and the outgoing mass flow is shown in [7]. If the passenger compartment is considered as a holistic system, the following heat flow balance results:

$$\dot{Q}_{HV\,AC} + \dot{Q}_{loss} + \dot{Q}_{body} + \dot{Q}_{trans} = 0 \tag{1}$$

The heat flow from the HVAC system $\dot{Q}_{HV\,AC}$ can be calculated with the air mass flow $\dot{m}_{air}$, the specific heat capacity $c_{p,air}$ and the temperature difference ΔT.

$$\dot{Q}_{HV\,AC} = \dot{m}_{air} * c_{p,air} * \Delta T \tag{2}$$

The other heat fluxes, like convection, radiation and heat conduction, are calculated as described in [19].

B. *Influence of Solar Radiation*

The solar radiation entering the vehicle interior through the glazing heats up the interior of the vehicle, which additional heats up the air inside the vehicle cabin. As described in [14] it is possible to determine the sun's position through the day depending on the rotation around the north axis. The angle between the sun and the north axis is called azimuth (α_{sun}). To calculate which masses and which exterior surfaces of the vehicle cabin are heated up by the sun, it is necessary to calculate the relative angle between the sun and the vehicle. Figure 1 shows the relative rotation between the sun and the vehicle. The angle between the vehicle and the sun $\Delta\alpha$ is the difference between

$$\Delta\alpha = \alpha_{vehicle} - \alpha_{sun} \tag{3}$$

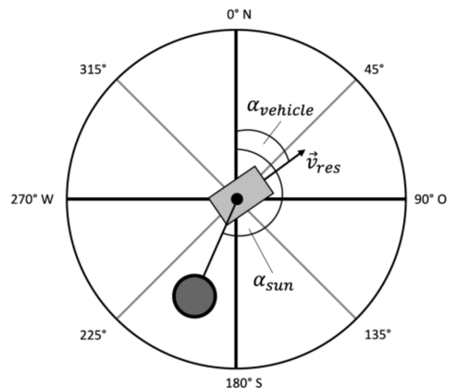

Figure 1. Relative rotation between a vehicle and the sun.

From $\Delta\alpha$ can be derived which surface and which window is heated up by direct solar radiation. If $\Delta\alpha$ is equal to zero or 180° the sun is directly in front or back of the vehicle and these are the only surfaces which are shined. If $\Delta\alpha$ is not equal to zero more than one reference surface is irradiated and depending on the value of $\Delta\alpha$ the shined surfaces are calculated in a look-up-table. The sun position is calculated as described in [14] and the solar intensity depending on date and time can be provided for different regions worldwide. For this paper, we will use Karlsruhe in Germany as an example, data provided by [4].

C. *Model of the vehicle cabin*

The vehicle interior is modelled as an air volume with a homogeneous air density and temperature distribution. The interior temperature depends on the incoming heat fluxes from the interior walls of the vehicle cabins and the incoming solar radiation. Furthermore, the interior temperature is increased, reduced or kept constant by the heating/air-conditioning system. The design of the vehicle interior model is based on the model by [11] but is adapted with regard to the model's own requirements.

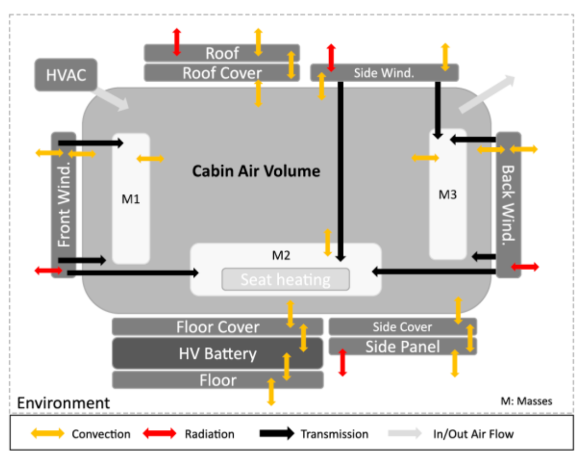

Figure 2. Design of the vehicle cabin model. Displayed are all modelled surfaces, masses and heat exchange mechanisms.

Figure 2 shows the design of the vehicle cabin model and all heat exchanging processes that appear in the vehicle cabin.

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The external surfaces of the vehicle are in heat exchange via radiation (red arrows) and forced convection (yellow arrows). There are three glass surfaces in the vehicle cabin: Front window, side windows and back window. Through the glass surfaces, solar radiation is emitted into the vehicle cabin (black arrows). All incoming and outgoing heat flows are balanced via the cabin air volume. The temperature of the cabin air volume can be calculated with [1][11].

$$\Delta T = \int_0^t \frac{\dot{Q}_{air}}{m \cdot c_{p,air}} dt \tag{4}$$

Using (4), it is possible to calculate the surface temperatures of the vehicle cabin. For the calculation of the heat exchange coefficient, the vehicle cabin is simplified as a cylinder [2] and calculation of the coefficient is done with the methods from [19]. The solar radiation hitting the inclined surfaces $E_{dir,tor}$ can be calculated with the help of the direct horizontal solar radiation $E_{dir,hor}$ from the data from [4], the torsion angle of the surface θ and the solar elevation γ_{sun} [14]:

$$E_{dir,tor} = E_{dir,hor} * \frac{\theta}{\gamma_{sun}} \tag{5}$$

For a detailed calculation of θ see [14]. The diffuse solar radiation $E_{dif\ f,tor}$ can be estimated with an isotropic approach using the horizontal diffuse radiation from the data $E_{dif\ f,hor}$ and the rotation angle of the surface $\gamma_{sur\ f}$.

$$E_{dif\ f,tor} = E_{dif\ f,hor} * 0.5 * (1 + \cos \gamma_{sur\ f}) \tag{6}$$

The calculation of a projected surface, as in [7], is dispensed with in favor of the model complexity. The fraction of radiation which enters the vehicle cabin through the glazed surfaces is determined by the transmission coefficient τ. The radiation entering the cabin is calculated as a product of the sum of the diffuse and direct radiation times τ and the surface area A.

$$Q_{through} = (E_{dif\ f,tor} + E_{dir,tor}) * \tau * A \tag{7}$$

It is assumed that the passengers are sitting and remain calm which results in heat flow from the passengers of 58 $\frac{W}{m^2}$ [15]. Depending on the height and weight of the passenger the surface area of the passenger can be calculated with the Mosteller equation, which can be found in [18].

D. *Controlling of the HVAC-System*

The HVAC system can be operated in three different operational modes. In the preset mode, it is possible to set the desired cabin temperature and the inlet mass flow. The maximum mass flow of the HVAC system is in this case 9 $\frac{kg}{min}$. The Min/Max - Mode aims to heat/cool down the vehicle cabin as fast as possible. If the temperature difference between the set temperature and the actual temperature is smaller than 3 K, the HVAC power is reduced. The automatic mode is modelled using the comfort perception of an average passenger. The comfort perception is described in [3] and can be modelled with the equations of [2]. The comfort perception is depending on the environment temperature, see Figure 3. Independent from the operation mode, the inlet air temperature is controlled by a PI - Controller. A Proportional–Integral–Derivative (PID)-controller has no significant advantage compared to a Proportional–Integral (PI)-controller because of the big thermal internal of the vehicle cabin [11]. A PI-controller is also used in the model of [13] to control the Air Conditioning (AC)-compressor. The power demand of the air conditioning is calculated using the Coefficient of Power (COP). The data comes from a comparable air conditioning system [10]. Using (8), the electric power demand P_{el} can be calculated.

$$COP = \frac{\dot{Q}_{HV\ AC}}{P_{el}} \tag{8}$$

The electric power demand when heating is calculated via a characteristic map using the output of the controller as input. The electric power demand is calculated as the output variable of the characteristic map. The characteristic map is constructed heuristically with data from [11] where the same HVAC system is modelled.

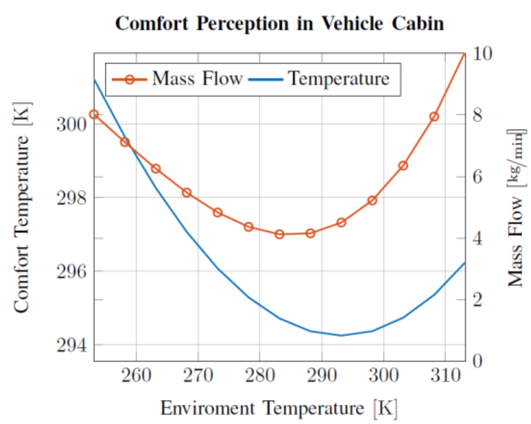

Figure 3. Comfort temperature and mass flow perceived as pleasant in the vehicle interior as a function of the ambient temperature. Calculated with the equatiosn from [2].

E. *Modelling the other auxiliary consumers*

Auxiliary consumers are divided into four categories: continuous (e.g., electronic control unit), comfort (e.g., radio and window heating), dynamic (electrical power steering), and switched consumers (can be switched by driver). Kruppok has published measured power values of the auxiliary consumers, which are used in this model, since the same electric vehicle is modelled [11].

The low beam in this model is switched on and off automatically. A distinction is made between summer and winter. In winter, the low beam is switched on automatically between 5 p.m. and 9 a.m. In summer mode, the period is shortened to the time between 8 p.m. and 6 a.m. From visibility of less than 150 m, the low beam is also switched on.

If the low beam is switched off, the daytime running lights are switched on as required by the Road Traffic Act [17]. The indicators are turned on when the internal CarMaker variable Vehicle on Junction is set and the steering angle is greater than 114.6°. The brake lights are turned on when the internal CarMaker Variable Brake is set. The wipers are used depending on the rain rate set before the simulation in CarMaker. The operation level is set automatically in the model. The Electric Power Steering (EPS) is modelled differently. Due to the highly dynamic power demand, the actual EPS power is calculated by a characteristic map.

IV. VALIDATION

The validation of the model includes, on the one hand, the validation of the heating/climate system and the associated thermal processes in the vehicle interior, and secondly the power requirements of the auxiliary consumers. Measurement data from the literature are used for validation. There are measurement studies of the temperature behavior of the vehicle cabin, which can be found in [6] and [11].

A. Validation of the Vehicle Cabin Model

The An essential component of the overall model with considerable influence on the temperature development in the interior is the vehicle cabin model. For the validation of the vehicle cabin model, the heating behavior of the interior is observed without air conditioning, without solar radiation and without wind. The measurement data used is taken from the work of Kruppok [11]. The test vehicle is pre-tempered to 275.5 K for a sufficiently long time, so that it can be assumed that each component has the same temperature. Subsequently, the vehicle is transferred to an environment with an ambient temperature of 291 K and the heating behavior of the interior is measured. The temperature is measured at different places inside the vehicle cabin and is averaged for validation. The vehicle is stationary and there is no irradiation from the sun. The same is also simulated in the model. To describe how well the model reproduces the experimental data, the coefficient of determination R2 is shown in (9). A detailed derivation of the coefficient of determination can be found in [5].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \qquad (9)$$

The coefficient of determination lies between $0 \leq R^2 \leq 1$. A value of zero indicates that there is no correlation between the measured values and the model, whereas a value of 1 can only be achieved if the measured values also describe the model at the same time. For the validation of the vehicle cabin model, the coefficient of determination between the heating curve of the model and the measured values is calculated. Optimal is a value close to one. By adjusting the heat transfer coefficients of the vehicle cabin model, a coefficient of determination of approx. 91.1% is achieved. Figure 4 shows that the heating of the interior is faster in the model than in the measurement, but the same final temperature is reached in both cases. For the determination of the energy demand of the air conditioner without taking comfort aspects, the interior model is considered to be sufficiently accurate.

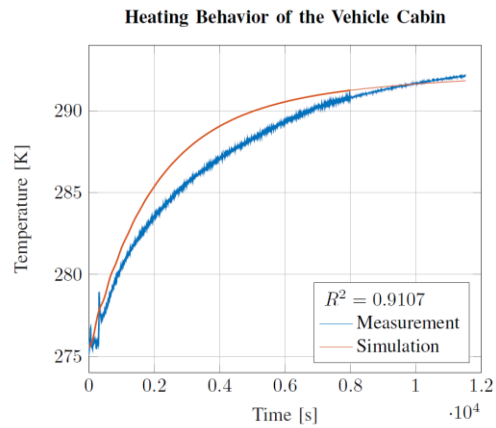

Figure 4. Heating of interior without air condit. with pre-heated interior.

B. Validation of the HVAC

Investigations by Kruppok have shown that the required inflow temperature of the air flowing into the vehicle, cabin is not achieved immediately after the heating/air-conditioning system is switched on [11]. Due to the thermal inertia of the system, it takes approx. 1000s (about 17min) until a stationary final temperature is reached. The behavior of the inflow temperature can be approximated by a transfer element with a second-order delay (PT2 element). The result is a well-fitting temperature curve in the model compared to the measurement data, see Figure 5.

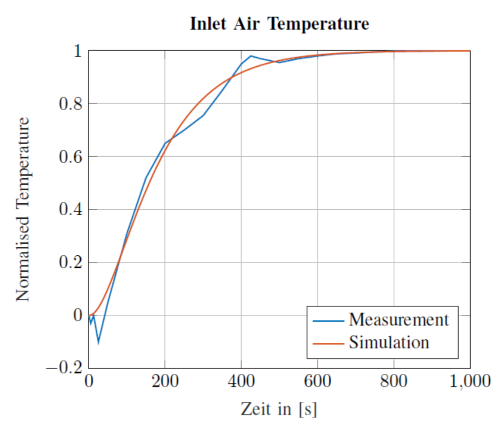

Figure 5. Heating of the interior without air conditioning with pre-heated interior.

It is assumed that the same behavior occurs in the heating mode because the HVAC is operated as a heat pump when in heating mode. So, the same components are in operation. By validating the heating behavior of the vehicle cabin model, the entire HVAC system, but especially the controller setting can be validated. As a reference, a measurement in which the interior temperature is recorded with active heating. This is the same as the average temperature, determined in the model. The test vehicle is pre-conditioned to 266.2 K and the target temperature of the interior is 297.2 K. The measurement data is published in [6]. In the preset mode, the temperature behaves like the real-world measurement. The heating system is operated with the maximum mass flow of 9 $\frac{kg}{min}$.

A similar mass flow is also used for the measurement, due to the low ambient temperature and the preconditioning of the vehicle. In the real vehicle, there is a clear overshoot of the interior temperature. This is avoided in the model by controller setting. The target temperature is reached at the same time after approx. 800s. The steady-state final temperature of the simulation is a few tenths of a Kelvin higher than the setpoint temperature, but this deviation reduces in the further course of the simulation. In min/max mode, the setpoint temperature is reached much earlier, as desired. A stationary final state is already reached after approx. 400s. This is achieved by a maximum temperature of the incoming air and a maximum air mass flow. The validation of the heating-up behavior shows that the model can be used to simulate the real vehicle interior very well. Through the different operating modes, it is possible to simulate different scenarios.

C. Validation of The Energy Consumption

In his work, Gutenkunst carried out five test drives of Bruchsal - Karlsruhe - Bruchsal and measured the distance travelled and the energy consumption [8]. Those measured data is used as a reference for the results of the simulation. In the simulation environment, the model has calculated with the air conditioning switched off, in good visibility, without rain and during the day. During the simulation, the local speed limits along the route are adhered to exactly. Table I shows the results of the measurement runs and the simulation.

TABLE I. COMPARISON ENERGY CONSUMPTION. MEASUREMENT DATA ARE TAKEN FROM [8].

Number	Distance [km]	Measurment Energy [kWh]	Measurment Consumption [kWh/100km]	Simulation Energy [kWh]	Simulation Consumption [kWh/100km]
1	56.92	7.77	13.65		
2	56.87	9.72	17.08		
3	56.29	9.95	17.62		
4	57.24	9.44	16.50		
5	57.62	10.17	17.65		
∅	56.99	9.41	16.50	9.67	17.31
Deviation of ∅				**2.78 %**	**4.89 %**

The normalized energy consumption in the simulation is approx. 5% higher than the average consumption of the measurement runs. This is due to the following reasons: The route length in the simulation already deviates 1.94% from the average real route length. The reason for this is the inaccuracy of GPS data, with which the route was created in CarMaker. Since the normalized consumption results from the total energy demand and the route, there are deviations. The pure energy demand is also higher in the simulation despite the shorter route. The reason for this is the unknown use of the auxiliary consumers and a possible velocity deviation during the measurement. Since the deviation in the simulation to the measurement is less than 3%, it can be assumed that the general calculation of the energy consumption is sufficiently accurate. The data from measurements two to four are done with normal traffic. Since the traffic is not modelled in the simulation the comparison between measurements two to four and the simulation are expected to be better. The comparison shows a deviation of only 0.33% for the comparison of total energy consumption. The normalized consumption is now only 1.4% higher than in the measurement.

D. Validation

The energy consumption of the HVAC system in the heating case is validated with the data from [11]. Since a similar HVAC model for the same reference, the vehicle is described in [11], the comparison is legitimate. The power demand in the heating case in the model of the present work is determined via a characteristic map. The map is developed heuristically. The input variable of the characteristic map is the output of the controller, which describes the extent to which the temperature of the incoming air must be increased by the heating system. The output variable is the electrical power in Watts. The energy consumption calculation is carried out in the time frame of the WLTP cycle. Figure 6 shows the result of the validation with different ambient and target temperatures in the vehicle cabin.

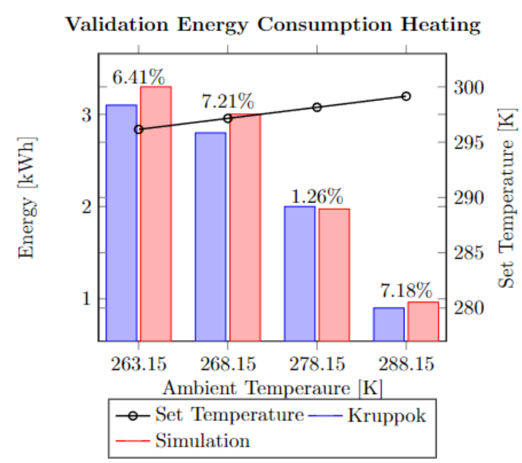

Figure 6. Validation of the energy consumption in the heating case at different ambient temperatures in the WLTP cycle. Comparison data are taken from [11].

The percentage values above the bars describe the relative deviation between the simulation and the data from [11]. The approximation of the power demand of the heating system via a map provides sufficiently accurate matches to the data from the literature. The relative deviation is in all cases smaller than 7.25%. At low ambient temperatures, however, the energy consumption in the simulation is higher than in [11]. One possible reason for this is deviating heat transfer coefficients, which lead to increased heat loss from the vehicle cabin at low ambient temperatures. The heat transfer coefficients in [11] are not fully known.

V. DISCUSSION AND CONCLUSION

The validation shows a good result if the model is compared with data from the literature. The deviation is relatively small and is, therefore, acceptable for the objective of this work. The model construction of the HVAC system is based on similar models, which can be found in literature, e.g., [1],[11] or [16]. The aim was to build a simpler model with at least nearly good simulation results as other, more complex models. This is achieved but only validated for the heating case. In addition, the calculation of the power demand of the heating system with a characteristic map is not very accurate although it works well in this case. A detailed measurement of real currents would bring more accurate information into the model. But overall, the investigation has shown, that the model results are quite accurate for the cases investigated. With more detailed data from the reference vehicle, especially for cooling cases and the explicit use of different auxiliary consumers the model can be updated to a more detailed model with a highly accurate energy consumption calculation.

The auxiliary consumer model makes it possible to determine the energy consumption of all the auxiliary relevant in an electric vehicle. The model shows good agreement with measured data which can be found in the literature, despite its simplifications and assumptions and with considerably less modelling effort. The deviation of the energy consumption of the heating system to values from the literature is less than 8% and the consumption of the other auxiliary consumers deviates only 0.33% from the measured values. At the same time, the structure of the model makes it possible to link the model to the simulation tool CarMaker. Via the interface between the model and CarMaker, it is possible to connect other models, such as an EMS, to the auxiliary consumer model. This work has shown that even a less detailed model can produce similarly accurate results about the energy consumption of the auxiliary consumers than detailed models.

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