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Invited paper

ENERGETIC PROPERTIES OF THE (FAST) CHARGING AND DRIVING OF AN ELECTRIC VEHICLE – A RAGONE ANALYSIS

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Abstract. *The energy efficiency of EVs is analysed for the charging and for the driving process where real parameters of a product of the automotive industry are considered. The efficiency in the charging mode is analysed and represented in function of the charging time. The maximum charging power allowed by the manufacturer is defining the lowest efficiency. After the calculation in a situation with an ideal charging station the influence of the resistance of the charging cable is taken into consideration. For the driving mode, the efficiency is estimated with the help of a special tool called "The Theory of Ragone plots". The driving efficiency is calculated for the maximum possible propulsion power of the car, and represented in a dimensionless Ragone representation. The rated power of the car is represented in reference to the maximum possible power that can deliver the car battery.*

Key words: *EV battery, energy efficiency, charging time, driving efficiency, Ragone representation*

1. INTRODUCTION

During the next decade, Electric Vehicles EVs are expected to grow rapidly in the scene of the individual transportation worldwide, in order to reduce significantly the greenhouse emissions which are responsible for the climate change. In comparison with internal combustion engines (ICEs) vehicles, EVs have not only zero emission propulsion system but present a significant higher energy efficiency. The zero-emission characteristic must however be considered in a context where the electric power is coming from renewable sources or from nuclear plants. One of the typical disadvantages of EVs concerns the relatively long charging time which is not able to compete with as well ICE vehicles as fuel-cell and Hydrogen propulsion systems. With the aim to overcoming this handicap the automotive industry has spent many efforts for allowing a fast charge, where the battery cooling has been specially designed. Other important efforts have been made in the field of the power distribution and of the charging infrastructure [1,2]. Fast charge of

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a battery means a high power or high current causing losses in the internal series resistance of the battery elements and in the charging cable. These losses will be analysed in the present paper in dependency of the charging power and charging time and a corresponding energy efficiency will be calculated. Fig. 1 shows the structure of the analysed system with the charging station, the car battery and the electric propulsion system. The efficiency of the charging process is indicated in the figure (η_{ch}).

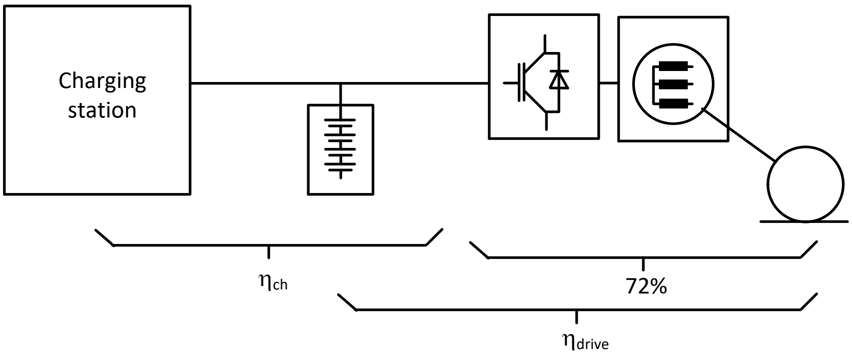

Fig. 1 Electric vehicle with the charging station

For the driving mode of the EV the maximum power level is defined according to a performance criterium which makes the EV's competitive with the actual standard performances of ICE vehicles. This means that the power limit is chosen as high as possible for a given battery capacity. The present paper tries to characterise the energetic performance of the driving mode of the EV and will use a specific method called the Theory of Ragone plots [3, 4]. The Ragone plot indicates additionally the theoretical performance limit of a given battery as the maximum extractable power in the discharge mode. The efficiency of the driving mode is indicated in Figure 1 (η_{drive}).

The present study is realized on the base of available battery parameters and should induce further investigations, especially in the direction of always higher charging powers as indicated in Table 1.

Table 1 Actual and future battery capacity and charging power

Manufacturer	Battery name	Capacity	Charging power
Porsche	Macan	95kWh	270kW
Zeekr	Golden Brick	75kWh	500kW
Catl	Quilin	100kWh	600kW

2. ENERGY EFFICIENCY

2.1. A general model for the efficiency

The quality of a storage system is quantified through its energy efficiency, taking into the account the internal losses during charging and discharging, the self-discharge effect during the time the energy is maintained in the storage device, even if the exchanged power is set to zero. In some specific cases, the energy needed for the auxiliaries must be considered. These auxiliaries are for example the circulating pumps of a vanadium redox flow battery (VRB), the vacuum pumps of a flywheel for the reduction of the aerodynamic drag, or the cryogenic system of a superconductive magnetic energy storage device (SMES). Figure 2 shows the energy flow of a storage system where all the listed effects are represented [5]. For an internally stored amount of energy, the primary needed amount can be significantly higher (Energy to be stored). The typical example of this mechanism is analysed in the following sections for electrical vehicles when so called Ultra-Fast Chargers are used. Similarly, at the output of the storage system, the recovered energy can be strongly reduced in comparison with the initially existing amount of accumulated energy. The penalty in the discharge process will further be illustrated using the "Theory of Ragone Plots".

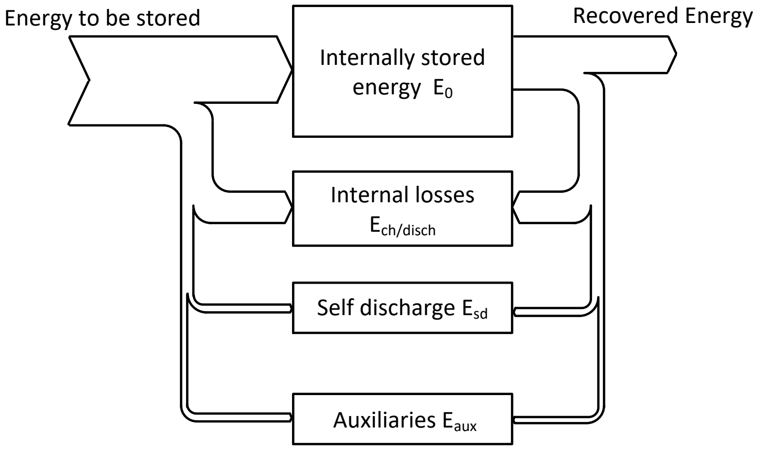

Fig. 2 Energy flow and losses in the transfer to and from an energy storage device

2.2. Structure and parameters of an example of EV

The aim of the present analysis is to set in evidence the real behaviour of the charging and driving of an EV vehicle. A quantitative estimation of the energetic performance must be based on a true example of the actual automotive industry. The example of the Volkswagen ID3 is chosen [6].

The structure of the ID3 battery is given in Fig. 3 with its serial connection of 9 modules, each composed of a parallel connection of 2 times 12 elements in series. Figure 4 is an equivalent circuit of one element where the local parameters are defined. The internal resistance of the elements R_{ielem} is equal to 1.857 mΩ and the internal voltage source U_{0elem} is chosen at 3.59V. This value represents an average value of the variable voltage which in reality depends on the state of charge. The charge of one element is given as Q_{0elem} = 74.76Ah. The energy stored in one element can be calculated as

$$E_{elem} = U_{0elem} \cdot Q_{0elem} = 3.59V \cdot 74.76Ah = 268.5Wh \quad (1)$$

With the series number of modules and their internal connection the total number of elements is

$$n_{el} = 9s(12s/2p) = 216 \tag{2}$$

And the total energy capacity of the car becomes:

$$E_{bat} = 216 \cdot 268.5Wh = 57.97kWh \tag{3}$$

which value confirms the indicated nominal capacity of 58kWh on the nameplate.

For the internal voltage of the car battery, there are 216/2 elements in series. The voltage becomes:

$$U_{0bat} = 216/2 \cdot 3.59V = 387.7V \tag{4}$$

The internal resistance of the car battery is

$$R_{ibat} = 108/2 \cdot 0.001857\Omega = 0.1003\Omega \tag{5}$$

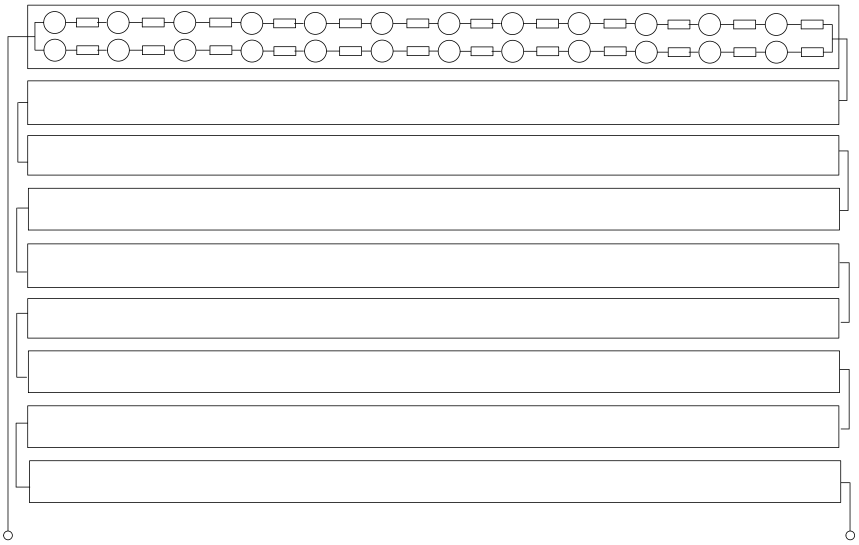

Fig. 3 Structure of the ID3 battery

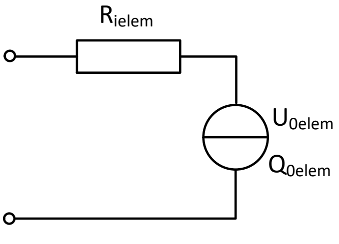

Fig. 4 Equivalent scheme of one battery element

3. THE CHARGING EFFICIENCY OF THE ID3

3.1. Equivalent scheme

For the evaluation of the energetic performance of the charging process, the equivalent scheme of Fig. 4 will first be considered, and the performance of the charging of the car will be calculated. Further the influence of the connecting cable will also be estimated. The corresponding equivalent scheme for the charging process is given in Fig. 5.

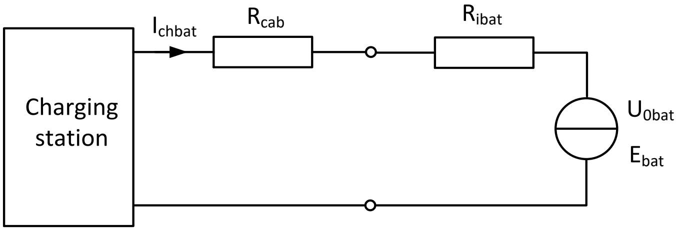

Fig. 5 Equivalent scheme of the charging process

3.2. Energetic performance

The energetic performance of the battery is calculated in dependency of the charging time t_{ch}.

First, the charging power is calculated internally of one element (P_{i_elem}).

$$P_{i\_elem}(t_{ch}) = \frac{E_{elem}}{t_{ch}} \tag{6}$$

Then, the internal losses on the series resistance are calculated with the help of the charging current:

$$I_{ch\_elem}(t_{ch}) = \frac{P_{i\_elem}(t_{ch})}{U_{0elem}} \tag{7}$$

The external power of one element corresponds to the sum of the internal power and the resistive power dissipation.

$$P_{e\_elem}(t_{ch}) = P_{i\_elem}(t_{ch}) + R_{i\_elem} \cdot I^2_{ch\_elem}(t_{ch}) \tag{8}$$

The two curves of the internal and the external power of one element in dependency of the charging time are represented in Fig. 6. The values of the powers are represented for a charging time range comprised between 4 hours and 6 minutes. After the value of 2 hours of charging time, the curve is very flat. But under the value of half an hour, the power increase is very steep.

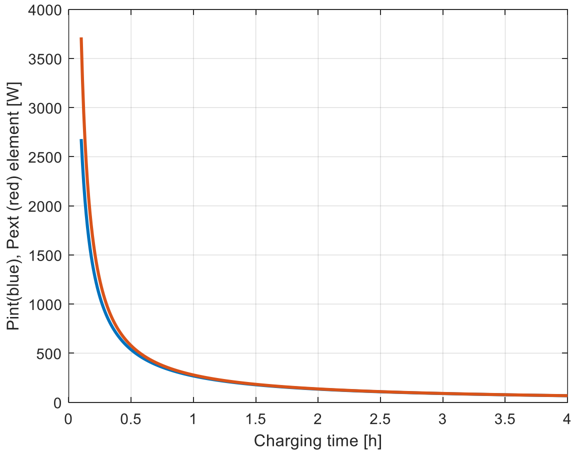

Fig. 6 Internal and external charging power in function of the charging time

Then, the efficiency of the charging process is calculated also in function of the charging time. The efficiency is calculated as the ratio of the internal power to the external one:

$$\eta_{elem}(t_{ch}) = \frac{P_{i\_elem}(t_{ch})}{P_{e\_elem}(t_{ch})} \tag{9}$$

Figure 7 shows the curve of the charging efficiency in an ideal case where the influence of the cable resistance is neglected. The curve shows that the efficiency is over 90% for a charging time above one third of an hour. For charging times under 15 min, the efficiency becomes problematic.

The charging current delivered to the car from the charging station is equal to the double value of the current in the battery elements (2 parallel ways):

$$I_{ch\_\mathrm{bat}}(t_{ch}) = 2 \cdot I_{ch\_\mathrm{elem}}(t_{ch}) \tag{10}$$

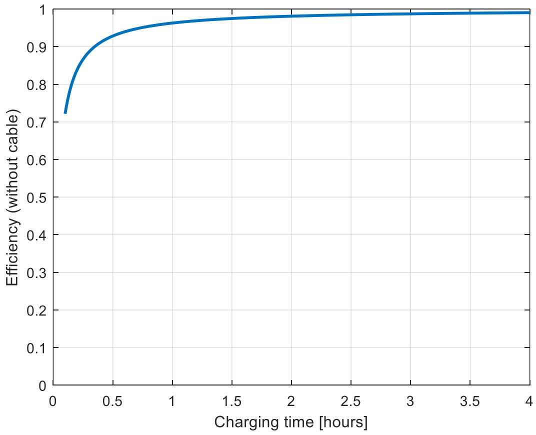

Fig. 7 Charging efficiency in function of the charging time

The curve of the current delivered to the car is represented in Fig. 8. For a charging time of half an hour, the current reaches already the value of more than 250 A.

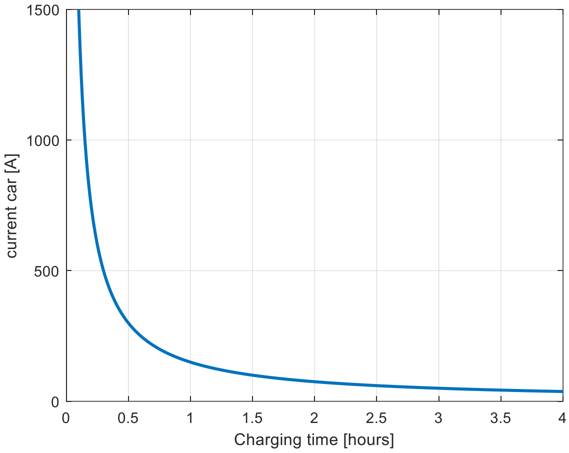

Fig. 8 Current delivered to the car in function of the charging time

And the power delivered to the car is:

$$P_{car} = 216 \cdot P_{\mathrm{e}\_elem} \tag{11}$$

It is also possible to define a car internal power if the equivalent internal resistance of the car is considered.

$$P_{i\_\mathrm{car}}(t_{ch}) = P_{\mathrm{e\_car}}(t_{ch}) - R_{i\_\mathrm{car}} \cdot I^2_{ch\_\mathrm{car}}(t_{ch}) \tag{12}$$

The two curves of the internal and external power of the car are represented in Fig. 9. The limited power level indicated by the manufacturer of 120kW is also indicated.

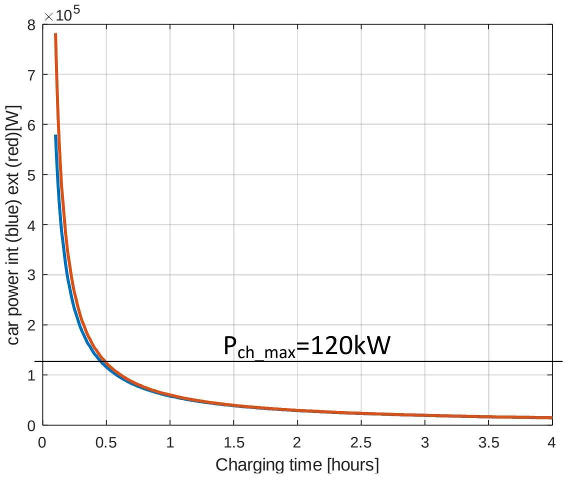

Fig. 9 Internal and external power of the car battery

Another criterium for the fast charge of the car is to have sufficient voltage from the charging infrastructure. Figure 10 indicates the minimum needed voltage to be able to provide the charging current.

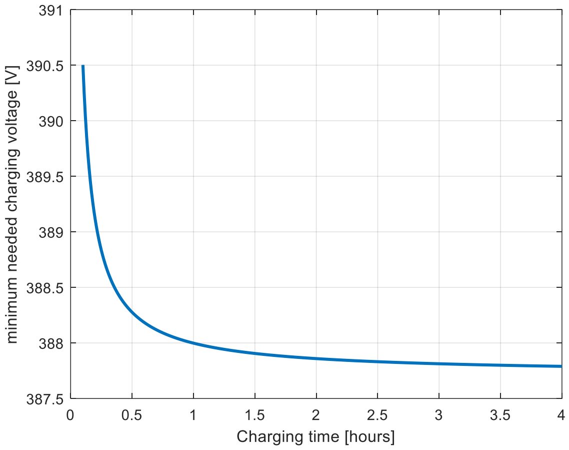

Fig. 10 Minimum charging voltage

3.3. The influence of the charging cable

Between the charging station and the EV a cable of 5m length with 70mm^2 section is considered [6]. With a value of the copper resistivity of 0.017 Ωmm^2/m, the equivalent resistance of the cable becomes:

$$R_{cab} = \frac{\rho \cdot 2 \cdot l}{s} = \frac{0.017\Omega mm^2 / m \cdot 2 \cdot 5m}{70mm^2} = 0.0024\Omega \tag{13}$$

$$P_{station}(t_{ch}) = P_{\text{i\_car}}(t_{ch}) + (R_{i\_\text{car}} + R_{cab}) \cdot I^2_{ch\_\text{car}}(t_{ch}) \tag{14}$$

The power delivered to the car has only slightly different energy efficiency if the resistance of the cable is considered or not. The two efficiencies are represented in Fig. 11.

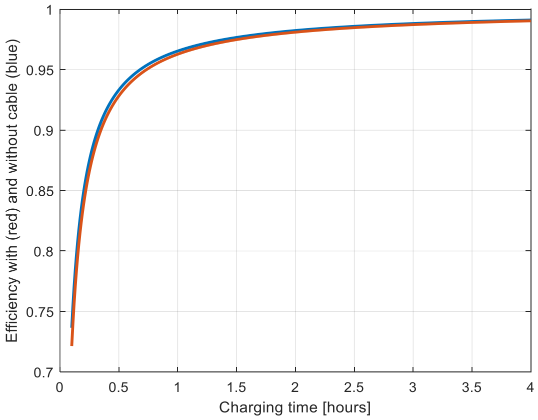

Fig. 11 Efficiency of the charging process with and without the influence of the cable resistance

4. THE EFFICIENCY OF THE TRACTION MODE

4.1. The equivalent scheme

For the evaluation of the efficiency of the traction mode the equivalent scheme of Fig. 12 is chosen. The efficiency corresponds to the ratio of the amount of energy transmitted to the propulsion to the amount of energy stored initially in the battery. This ratio can be calculated using the Theory of the Ragone plots [3, 4].

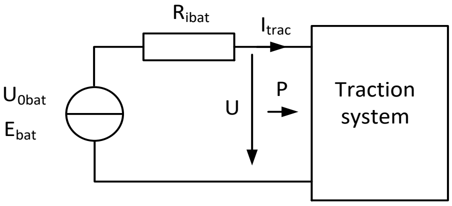

Fig. 12 Equivalent scheme for the traction mode

4.2. The theory of Ragone plots

This method applied to the discharge of an ideal battery under a constant power solicitation uses the basic relation between current and power for the equivalent circuit of Fig. 12. For the ideal battery the leakage resistor is neglected.

$$P = U \cdot I = (U_0 - RI)I \tag{15}$$

where U is the terminal voltage and I is the current. The solutions of the quadratic equation are:

$$I_{\pm} = \frac{U_0}{2R} \pm \sqrt{\frac{U_0^2}{4R^2} - \frac{P}{R}} \tag{16}$$

From the relations (15) and (16), and under the condition that the battery is empty at time $t_{inf} = Q_0/I$, the Ragone plot can be drawn. Q_0 is the initial charge related to the initial energy $E_0 = Q_0U_0$. The Ragone curve is the trajectory of the energy that can be transferred to the load when the discharge is driven by a constant power. The transmitted energy is depending on the power level of the exchange and can be calculated through rel. (17).

$$E_b(P) = P \cdot t_\infty = \frac{2RQ_0P}{U_0 - \sqrt{U_0^2 - 4RP}} \tag{17}$$

There is a maximum power, $P_{\max} = U_0^2 / 4R$ associated with an energy $E_0/2$. Relation 17 represents the section of the curve where the second solution of the expression of the current is considered (-sign) in the equation and corresponds to a power varied from a vanishing low value up to the maximum P_{max}.

The expression of the Ragone plot can be given with dimensionless units using the reference values

$e_b = E_b / Q_0U_0$ and $p = 4RP / U_0^2$ as

$$e_b(p) = \frac{1}{2} \frac{p}{(1 - \sqrt{1 - p})} \tag{18}$$

This expression is represented in Fig. 13 and corresponds to the trajectory of $e_b(p)$ when the power is varied. This variation can be produced by a variable resistance R_{load} which can be changed from an infinite value (open circuit) down to zero (short-circuited battery). The zero value of the current ($R_{load}= \infty$) corresponds to a zero power and is represented by the upper left end of the trajectory. Reducing the load resistance increases the current as well as the power but the energy extracted decreases. The power can be increased up to a maximum value of $P=U_0^2/4R$ corresponding to the right end of the figure (p=1). Then a further increase of the current up to the short circuit current corresponds to a decreasing power also to a strong reduction of the extracted energy. This second section of the curve (dotted line in Fig. 13) corresponds to the first solution of the expression of the current (+sign) in the equation (16). The double solution for the extracted energy for one single value of the power is an illustration of the double solution of the quadratic equation of the expression of the power as a function of the current (rel. 16). In Fig. 13 the point indicated (p=0.55, e=0.83) corresponds to the maximum power developed by the car with the example of the ID3 (150kW) as will be described in the next section.

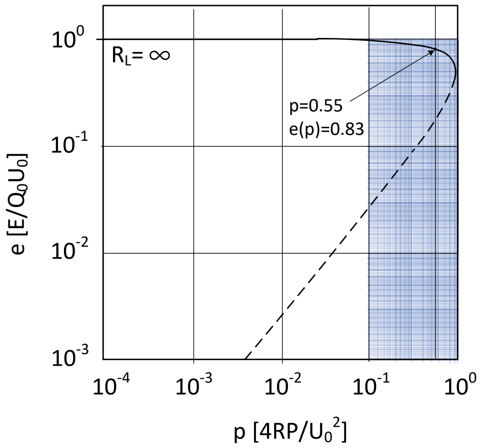

Fig. 13 The Ragone plot of the ideal battery in the dimensionless representation

4.3. The representation of the highest power of the ID3 in the Ragone plot

The name plate of the ID3 indicates a maximum traction power of 150kW. According to the definitions of the Ragone theory, the highest extractable power from the battery is given as:

$$P_{\max} = U_0^2 / 4R \tag{19}$$

At the level of the car, the parameters of an equivalent scheme according to Fig. 12 become:

$$U_{0\text{batt}} = n_s \cdot U_{0elem} = 108 \cdot 3.59\,\text{V} = 387.7\,\text{V} \tag{20}$$

$$R_{\text{ibatt}} = R_{ielem} \cdot 108 / 2 = 54 \cdot 0.001857\Omega = 0.1\Omega \tag{21}$$

From rel. 19, the maximum value of the power that can be extracted from the battery is calculated:

$$P_{\max} = (387.7V)^2 / 4 \cdot 0.1003\Omega = 374.7kW \tag{22}$$

When the mechanical power developed by the car is of 150kW, the extracted power from the battery is increased (divided by) the efficiency of the propulsion system (Fig. 1). The value 0.72 results from the efficiencies of the motor an of the converter (90% and 95%) and takes into the account the standby and idle losses (8%) as of the driveline and of the auxiliaries (6%).

$$P_{\text{maxbatt}} = 150kW / 0.72 = 208.33kW \tag{23}$$

Then the dimensionless value of the power p becomes:

$$p = 208.332kW / 374.7kW = 0.55 \tag{24}$$

And the dimensionless energy

$$e = \frac{1}{2} \cdot \frac{0.55}{1 - \sqrt{1 - 0.55}} = 0.83 \tag{25}$$

These two values are reported in the dimensionless Ragone plot of Fig. 13. The parameter *e* can be interpreted as the efficiency of the battery discharge process. The value of 0.83 is only reached if the car is driven with a power of 150 kW what occurs very rarely.

4.4 .The energy efficiency of the driving mode

For the final value of the efficiency in the driving mode, the efficiency of the battery discharge is combined with the efficiency of the propulsion system:

$$\eta_{drive} = \eta_{disch\_batt} \cdot \eta_{prop} = 0.83 \cdot 0.72 = 0.597 \tag{26}$$

This result is valid for the maximum propulsion power but shows the realistic energy properties of the typical EV.

An extreme consideration would be to integrate into the energy balance the efficiency of the charging process. The charging efficiency (by maximum charging power of 120kW) multiplied by the discharging one (P_{prop}=150kW) and by the efficiency of the propulsion system becomes:

$$\eta_{drive\_s-to-w} = \eta_{ch} \cdot \eta_{disch\_batt} \cdot \eta_{prop} = 0.925 \cdot 0.83 \cdot 0.72 = 0.55 \tag{27}$$

This value would correspond to an equivalent efficiency “source-to-wheel” where the source corresponds to the electric distribution grid.

CONCLUSIONS

Electric vehicles tend to replace classical ICE vehicles with always larger battery capacities and shorter charging times. Fast charging has the consequence of internal losses and need an accurate analysis of the power to be provided by the charging station. Resultant energy efficiency has been calculated in function of the charging time. The influence of the resistance of the charging cable has only a small influence on the efficiency. For the driving mode, a dedicated method called the Theory of Ragone plots has been used for the evaluation of the efficiency in the driving mode of the vehicle. The design of the ID3 vehicle shows that the maximum power of the vehicle corresponds to 0.55 of the maximum extractable power from the battery. A resultant efficiency for this power level is of 0.83 for the battery discharge. The final value of the driving efficiency is of 0.597 when the maximum driving power is used.

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