Efficiency Considerations on Energy Storage Systems and Devices

Alfred Rufer*
EPFL Ecole Polytechnique Fédérale de Lausanne, Switzerland

Abstract
Renewable energy sources are characterized by their intermittent or changing production. To assume robust or predictable insertion into a power grid, storage devices or larger facilities must be added to assume acceptable dispatchability. Storage devices are designed for specific amounts of energy as well as a defined power capacity. The aim of this article is to study the energy efficiency of storage devices depending on the power level chosen for the charging and discharging processes. A global model for classification of different losses is presented, in which internal charge and discharge losses are taken into account as well as the self-discharge effect. The energy required for storage device auxiliaries such as pumps, fans or cryogenic equipment is also included in the loss model. The effect of multiple cascade transformations is then analyzed with the example of a water electrolyzer for the production of hydrogen intended to power a fuel cell in the energy recovery section. Next, a dedicated tool called Ragone plot theory is presented, in which the amount of possible energy to be extracted is evaluated based on the power exchanged. The method is illustrated by the examples of a simple battery and an electric vehicle. Battery charging time plays an important role in the overall energy balance of the system.

Keywords: Energy storage; energy efficiency; equivalent scheme; charging losses; discharging losses; self-discharge; auxiliary power

1. Introduction

In the context of the global warming due principally to the combustion of fossil resources, the sector of power generation migrates since several decades towards new renewable energy sources like photovoltaic generators or windmills. These sources are characterized by their intermittent operation or availability related to meteorologic, seasonal or daytime conditions. As a consequence, their integration into a dispatchable energy grid can only be realized with the help of adapted energy storage devices or facilities. Electrochemical solutions like modern batteries are currently following steep growth with always better performances in terms of energy density and power density, accompanied by higher reliability and more acceptable economy. Beside that tendency, other solutions issued from the domain of reversible physics are proposed like flywheels, gravitational systems, compressed air CAES, superconductive or capacitive electric storage systems [1]. All that classical storage solutions can be used in applications where the storage time is limited to tens or thousands of hours, sometimes much less, related to limited available place or volume occupied, or simply related to a non-realistic budget. Generally, the energetic efficiency of the classical storage systems is not considered as being problematic, because it is comprised in most of the cases between sixty and ninety percent. For applications where the expected storage time is in the range of thousands and more of hours like is encountered in the case of so-called seasonal storage, other solutions must be considered where multiple or complex transformations are involved like electrochemical transformations with the example of water electrolysis for the production of hydrogen [2, 3, 4, 5]. Other processes are also candidates for longer storage times. Synthetic fuels production in solar reactors where water and carbon dioxide are taken out of the ambient air have reached the state of pre-industrial installations [6, 7]. For this second category of storage with transformation into a different matter, the cascade of transformations for a round trip storage from electric power and back leads to problematic performance with efficiencies between twenty and fifty percents.

The energy density of a storage system or device is considered as one of the most important parameters for the selection of a storage solution well adapted to a given problem. The weight energy density or the volume energy density allow to design a storage system in regards to the needed amount of energy to be stored in dependency of the available place or admissible total weight. The energy density parameters generally specify the amount of stored energy, but does not give any information on the primary amount of energy needed for the achievement of the storage process, nor on the finally remaining energy amount for the user after the discharge process. Here comes the notion of energy efficiency, where a second parameter is considered namely the power density which is selected by the designer of the application. The power density or the absolute value of the power during charge and discharge of the storage device are inverse proportional to the charging or discharging time. A fast charge meaning a high power level of the exchange.

This paper proposes a general model for the evaluation of the energy efficiency of storage systems in general and illustrates the specific properties of real storage systems where the cascade of single transformations can lead to a degraded performance. Further on, the dependency of the energy efficiency on the magnitude of the power during charge and discharge of a storage device will be shown. A well-adapted tool called the Theory of Ragone Plots [8] is used here to set in evidence some remarkable effect in electrochemical batteries where for example the discharge power is subject to a clear limitation. The theoretical analysis will be completed by an evaluation of the properties of a real case, namely the energetic properties of fast charging of the battery of an electric vehicle (EV).

2. A general model for the efficiency of an energy storage system.

The quality of a storage system is quantified through its energy efficiency, which is defined as the ratio of the finally recovered amount of energy to the primary amount needed to achieve the charging process. It takes into 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 1 shows the energy flow of a storage system where all the listed effects are represented [9]. For an internally stored amount of energy, the primary needed amount can be significantly higher (Energy to be stored). A typical example of this mechanism can be seen in the sector of electrical vehicles when so called

Ultra-Fast Chargers are used [10]. 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.

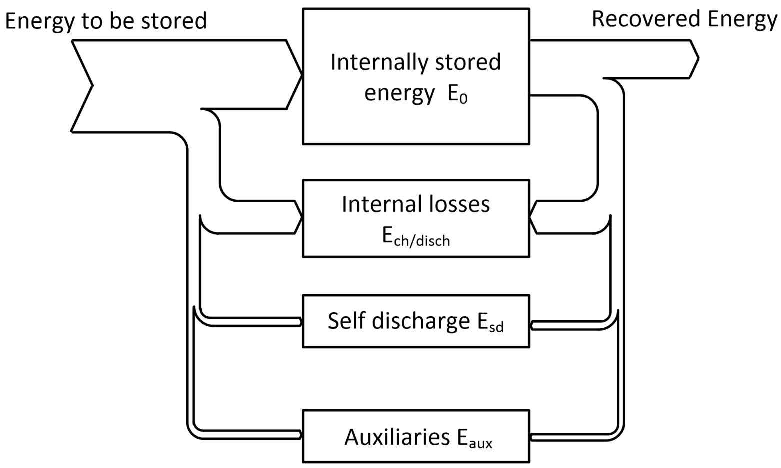
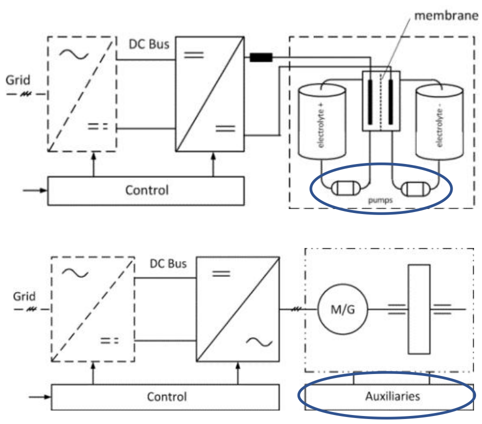
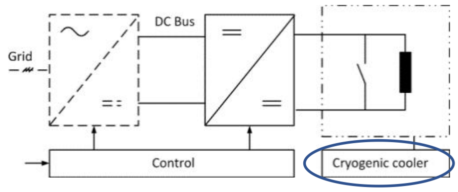


Fig. 1 Energy flow to and from a storage system

3. From a positive to a negative efficiency

In section 2, the energy needed for the system auxiliaries has been mentioned. Such auxiliaries correspond for example to the circulation pumps of a flow battery, to the vacuum pumps for the evacuation of the envelope of a high-speed flywheel. Superconductive magnetic energy storage must be assisted by a cryogenic equipment assuming the superconducting conditions (Fig. 2 left). The power consumed by all such auxiliaries should not be higher than the power available for the storage if the storage efficiency has to be kept positive.





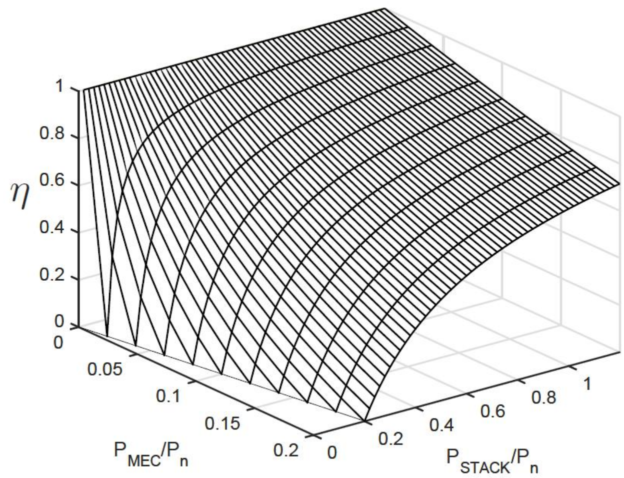


Fig. 2 Effect of the auxiliaries on the efficiency

For example, in the case of a VRB battery, the mechanical power for the electrolyte pumps has to be subtracted from the stack power (the battery itself is powering its auxiliaries) during discharge, and it must be added to the stack power during charge (the external source is powering the auxiliaries). If the charging time is identical to the discharging one, the round-trip efficiency becomes [11], [12].

$$\eta_{roundtrip} = \frac{\left(P_{stackdisch} - P_{mech}\right)}{\left(P_{stackch} + P_{mech}\right)} \tag{1}$$

From relation (1), it becomes evident that the round-trip energy efficiency can become negative (for example $P_{mech} > P_{stackdisch}$).

The variation of the round-trip efficiency in dependency of the charging/discharging power related to the nominal power of the battery P_n and in dependency of the related mechanical power P_{mech}/P_n is represented in Fig. 2 (right side). The operating range of the battery power is comprised between zero and 1.2 [p. u.], and the range of the needed related auxiliary power is comprised between zero and 0.2 [p. u.]. In Fig. 2, the negative values of the efficiency are only represented at the value of P_{mech}/P_n=0.2 in order to illustrate this property. A real operation of the storage system under such conditions would correspond to a non-sense.

4. The power-to-power storage system ESS (Electrical Storage System) based on Hydrogen

In Fig.3 an electrical energy storage system (ESS) is represented. In such a system, the input and output of the storage system is interfaced to an electrical distribution system or grid. The storage-form of energy, as well as the intermediate conversions are mentioned.

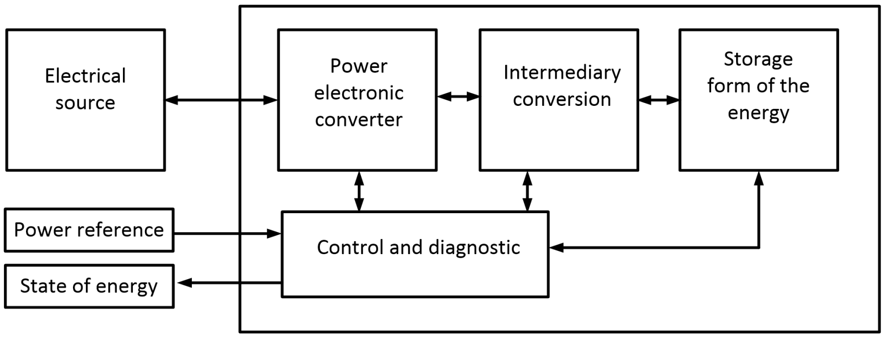


Fig. 3 General configuration of an Ess (Energy storage system

An ESS or power-to-power storage system based on hydrogen can be realized using a water electrolyser and a fuel cell for the intermediate conversions. In addition to these intermediate conversions hydrogen and oxygen conditioning systems are needed in order to elevate the volumetric energy density. Fig. 4 shows the elementary structure of an ESS based on hydrogen [1].

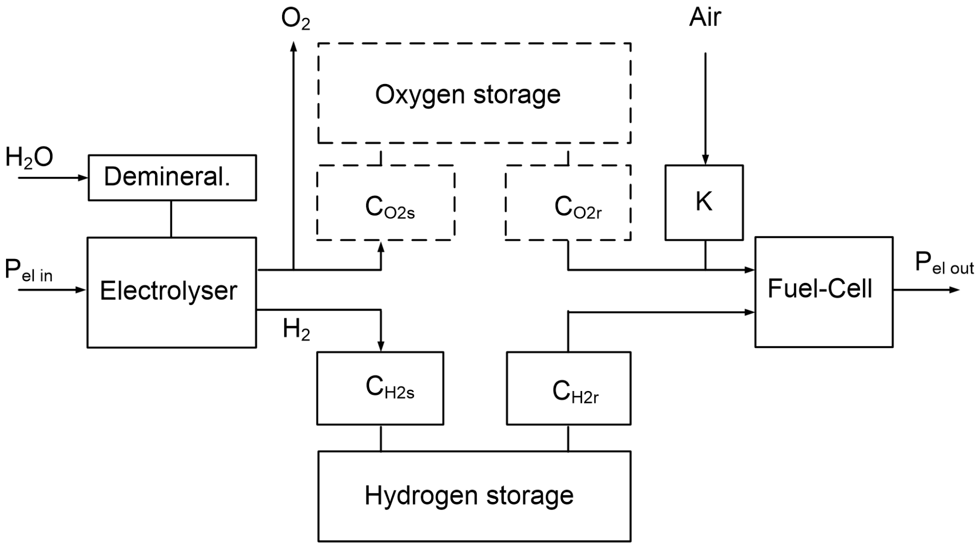


Fig. 4 Structure of a storage system based on hydrogen

In Fig. 4, the basic components of the system are the electrolyser, the hydrogen storage and the fuel cell. Between the electrolyser and the storage reservoir, a hydrogen conditioning device is represented (C_{H2s}), as well as between the storage reservoir and the fuel cell (C_{H2r}). The electrolyser produces also oxygen that can be stored. In Fig. 4, the oxygen path is represented in dotted line due to the fact that in a high number of modern fuel cells, the oxidation is achieved using the ambient air. For this purpose, an air compressor is represented (K). For the case of using stored oxygen, the conditioning blocks are represented (C_{O2s}, C_{O2r}).

The conditioning devices for the storage process (C_{H2s}, C_{O2s}) are generally compressors or liquefiers, while the recovery conditioning devices (C_{H2r}, C_{O2r}) are simple relieve valves. In the case of solid storage of hydrogen in the form of metal hydrides, the conditioning processes are more complex.

4.1 The overall efficiency of Hydrogen storage

The overall efficiency of the hydrogen storage is defined as the ratio of the electrical output energy to the electrical input energy and can be evaluated as

$$\eta_{global} = \eta_{elys} \cdot \eta_{con} \cdot \eta_{fc} = 0.55 \cdot 0.9 \cdot 0.5 = 0.247 \quad (2)$$

The use of electrolysers producing directly hydrogen under pressure, or high temperature electrolysers which can re-use the thermal dissipation of the fuel cell will lead to higher energy efficiency of the hydrogen storage.
Additionally, the storage of hydrogen or simply the use of fuel cells in the context of CHP (Combined Heat and Power) will increase the benefits of the use of hydrogen in energetic chains based on RES.

5. The Theory of the Ragone Representation

In general, a storage device is characterized through parameters illustrating the energy capacity and the power capability. Four parameters are defined as specific parameters as the weight energy density expressed in Wh per kilogram, the volume energy density expressed in Wh per liter, and the power-to-weight ratio or the power density expressed in W per kilogram and the volume power density expressed in W per liter. The energy density parameters give normally an information about the energy content per mass or volume unit at 100 percent of the State of charge (SOC). For the model represented in Fig. 1, the corresponding energy content is indicated as the internal stored energy amount E_0. For the evaluation of the primary energy needed to achieve the charging process (is indicated at the left side of this figure), as also for the finally recovered energy (right side of the diagram), additional information is needed. For the difference between these amounts, the most important influence is given through the second block indicated as internal losses $E_{ch/disch}$. These losses are generally depending on the intensity of the power during the exchange. The theory of the Ragone representation is a tool which allows to evaluate the possible amount of energy to be recovered in dependency of the power level. The next paragraphs will illustrate the behavior of electrochemical batteries, first for a simple small battery under variable power discharge where as well the power has a physical limit as also the efficiency follows a similar limitation. The second example will illustrste the limitations of an EV battery. The fast-charging process will be discussed in regards of the efficiency. In this case the charging losses can be covered by the charging infrastructure. But during driving, the discharge losses must be provided by the battery itself.

5.1 A first example of a battery discharge

With this first example, the power limitation during discharge will be illustrated. A small lead acid battery is considered with a no-load voltage of 12 Volt. The battery energy capacity is indirectly defined through its coulombic charge capacity defined as the current time integral, Q = 4Ah. The internal resistance of the total battery is R = 0.3 W. The battery is successively discharged and recharged under different values of power. In this case, the power level of the discharge is imposed through an external load resistor R_L. An equivalent scheme of the battery and its load is represented in Fig. 5.

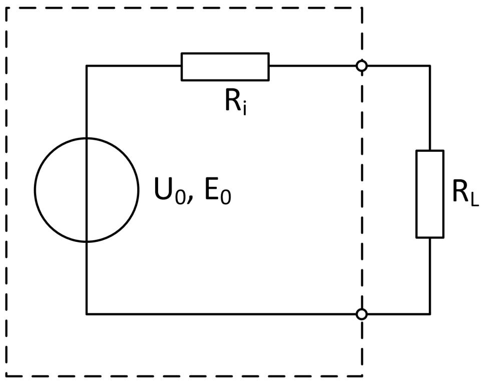


Fig. 5 Equivalent scheme of the battery and its load

The numeric values of Table 1 show the successive discharge conditions in terms of current I_L imposed by the corresponding resistance R_L. The power at the load side is calculated (rel 3) and its value in dependency of the current is represented in Fig. 6 The represented curve shows clearly the typical behavior of the power going through a maximum value and returning to zero for the short circuit condition.

$$P_L = R_L I_L^2 \quad (3)$$

R_L [W]	**I_L [A]**	**P_L [W]**	**P_i [W]**	**P_{tot} [W]**	**t_{dis}ch [s]**	**E_L [J]**
2.1	5	52.5	7.5	60	2880	151’200
0.9	10	90	30	120	1440	129’600
0.3	20	120	120	240	720	86’400
0.1	30	90	270	360	480	43’200
0.041	35	52.5	367	419.5	411	21’662
0	40	0	480	480	360	0

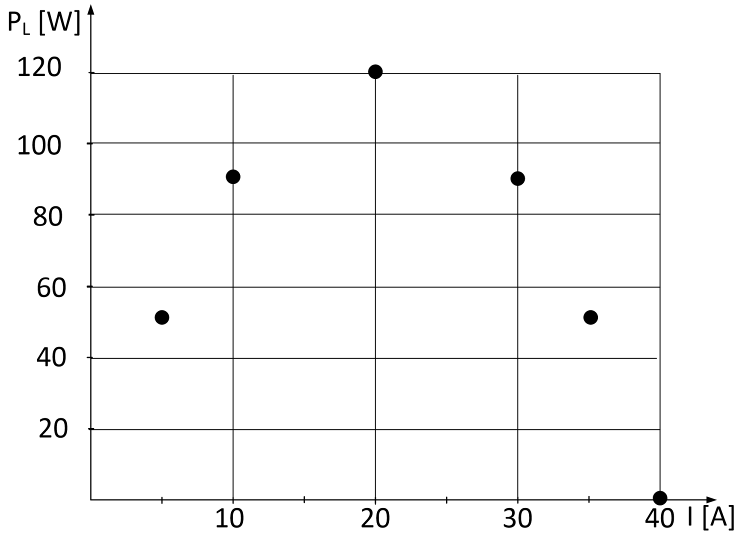


Fig. 6 Power at the load in dependency of the current

Then, the amount of energy transferred from the battery to the load is calculated according rel.(4) for all values of the discharge current.

$$E_L = P_L * t_{disch} \quad (4)$$

In this relation the discharge time is calculated through rel 5

$$t_{disch} = \frac{E_0}{P_i + P_L} \quad (5)$$

where the initially accumulated amount of energy is

$$E_0 = U_0 * C = 12V * 4Ah = 48VAh \triangleq 48VA * 3600s = 172'000J \quad (6)$$

and where the total discharge power is the sum of the internally dissipated one and the external one. The values of P_i, P_{tot}, t_{disch} and E_L are given in Table 1.
Figure 7 gives a first representation of a so-called Ragone plot, illustrating the variation of the energy transferred to the load in dependency of the power transferred.

$E_L=f(P_L)$

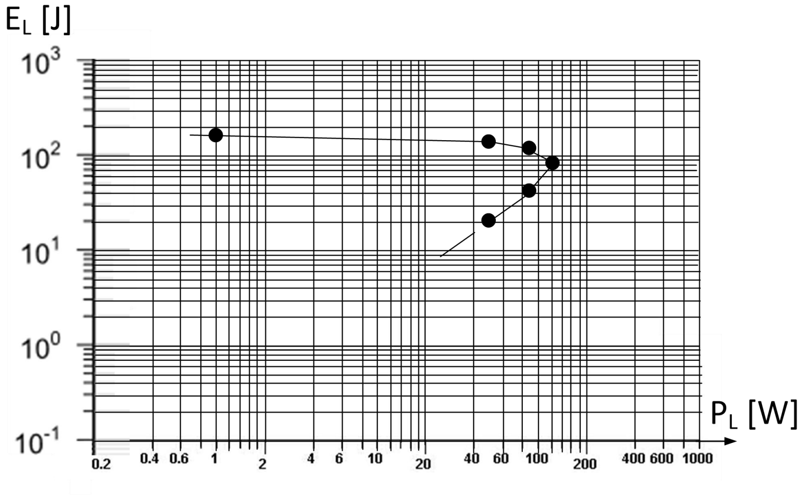


Fig. 7 Ragone plot of the small battery

5.2 The analytic form Theory of the Ragone Representation

A more general approach for the Ragone representation is based on the simple diagram of Fig. 8a where the energy storage device and the constant power load are represented [8]. This model can be used for the analysis of any storage system or device like a battery, a flywheel, a capacitive or an inductive electric system. As in the previous example of the electrochemical battery, an equivalent scheme is used for the analysis (Fig. 8b).

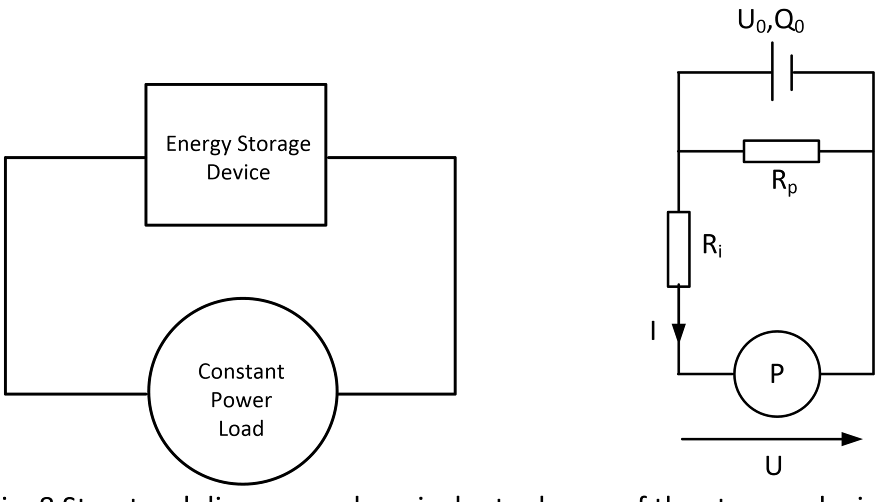


Fig. 8 Structural diagram and equivalent scheme of the storage device

The definition of the Ragone plot is given through the expression of the transferred energy to the load in dependency of the power according rel. 7.

$$E(P) = P \cdot t_{\inf}(P) \tag{7}$$

A first simplification of the battery model consists in neglecting the self-discharge effect and to consider the resistance $R_p = \infty$
And then the power at the load is calculated

$$P = U \cdot I = (U_0 - R_i I) I \tag{8}$$

The double solution of this quadratic equation becomes

$$I_{\pm} = \frac{U_0}{2R_i} \pm \sqrt{\frac{U_0^2}{4R_i^{\,2}} - \frac{P}{R_i}} \tag{9}$$

As the Ragone plot itself through rel. 10

$$E(P) = P \cdot t_{\infty} = \frac{2R_i Q_0 P}{U_0 - \sqrt{U_0^2 - 4R_i P + 2U_0 R_i / R_p}} \quad (10$$

The expression of E(P) can be translated into a relation in dimensionless units (13) using the definition of the base quantities:

$$e = E / Q_0 U_0 \tag{11}$$

$$p = 4R_i P / U_0^2 \tag{12}$$

$$e(p) = \frac{1}{2} \frac{p}{(1 - \sqrt{1 - p + 2R_i / R_p})} \tag{13}$$

The resultant Ragone plot of a battery can be drawn (Fig. 9)

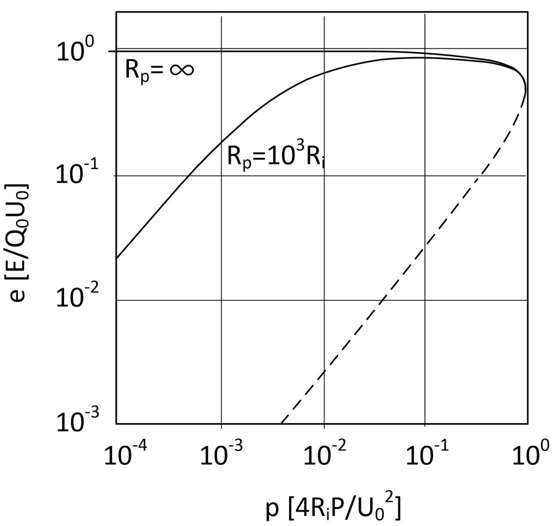


Fig. 9 Ragone Plot of a battery in dimentionless units

6. Energetic properties of the charging and driving of an electric vehicle

Electric vehicles are reputed for their better efficiency in regards to the classical ICE vehicles. Table 2 gives a comparison between these two systems from the point of view of their motor losses, the standby/idle mode losses and losses of the driveline and auxiliaries [13].

Efficiency of the propulsion system			
ICE propulsion		Electric vehicle	
Fuel in Tank-Gasoline	100%	Battery El energy	100%
Losses due to heat	62%	Losses El. Motor and converter (90% and 95%)	14%
Standby-Idle losses	17%	Standby-Idle losses	8%
Driveline losses	6%	Driveline and auxil.	6%
Tank-to-wheel efficiency	15%	Battery-to-wheel efficiency	72%

Table 2 Comparison of the efficiency of ICE and EV

A schematic representation of the propulsion chain of an EV is given in Fig. 10 where the efficiency of the charging process and of the driving mode are indicated. For the charging process the losses in the battery are considered. For the driving mode the discharge losses of the battery are combined with the efficiency of the propulsion system [14].

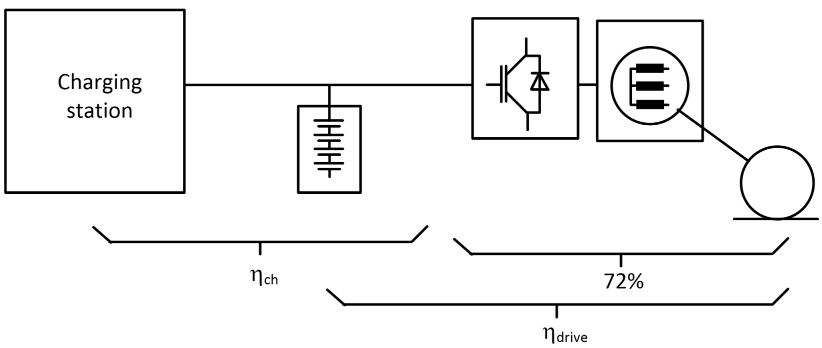


Fig. 10 Schematic diagram of an EV

6.1 Efficiency of the (fast) charging

For the charging of the battery of an EV the equivalent scheme of Fig. 11 is used. Between the charging station and the battery the resistances of the cable and the battery internal resistance are considered. In the whole range of the SOC , the internal voltage of the battery is considered as being constant. A very simple calculation is done for the power needed to reach a given charging time.

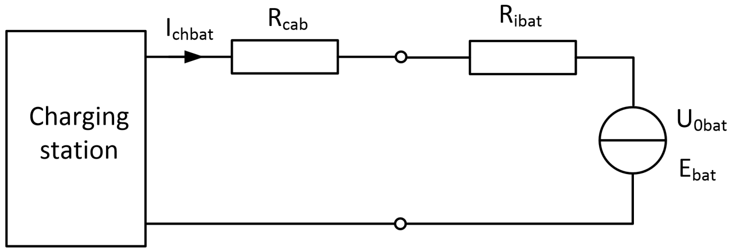


Fig. 11 Equivalent scheme of the charging process

First the power delivered by the charging station is calculated as a function of the charging time. The internal power of the battery is equal to the battery energy capacity divided by the charging time

$$P_{i\_\mathrm{batt}}(t_{ch}) = \frac{E_{batt}}{t_{ch}} \tag{14}$$

For the external power of the battery, the ohmic dissipation on the internal resistor is added

$$P_{\mathrm{e\_batt}}(t_{ch}) = P_{i\_\mathrm{batt}}(t_{ch}) + R_{i\_\mathrm{batt}} \cdot I^2_{ch\_\mathrm{batt}}(t_{ch}) \tag{15}$$

Where the charging current is calculated at the level of the internal voltage source

$$I_{ch\_\mathrm{bat}}(t_{ch}) = \frac{P_{i\_\mathrm{bat}}(t_{ch})}{U_{0bat}} \tag{16}$$

The curves illustrating the real behavior of the battery are based on a set of parameters of the Volkswagen ID3, namely a battery capacity of 58kWh and a battery no-load voltage of 388V [10]. The battery internal resistance is calculated for two parallel ways of each having 108 series connected cells [15].

$$R_{ibat} = 108/2 \cdot 0.001857\Omega = 0.1003\Omega \tag{17}$$

The curve of the power demand for charging is represented in Fig. 12 as a function of the charging time. The curve clearly indicates the very high power demand of the fast charging. In the figure, the maximum power of 120kW imposed as a limit by the manufacturer corresponds to a charging time of half an hour.

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. The figure shows in addition the influence of the resistance of the charging cable.

$$\eta_{bat}(t_{ch}) = \frac{P_{i\_\mathrm{bat}}(t_{ch})}{P_{e\_\mathrm{bat}}(t_{ch})} \tag{18}$$

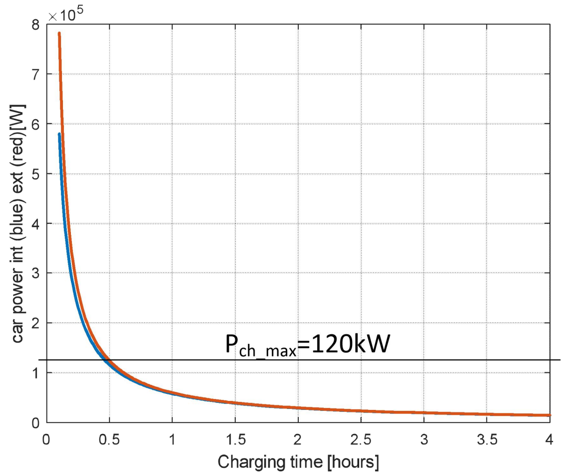


Fig. 12 Internal and external power

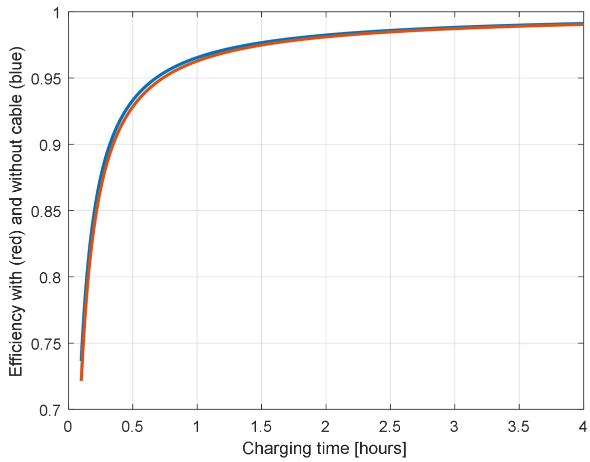


Fig. 13 Efficiency w and wo cable

6.2 Efficiency of the driving mode

The driving mode of a vehicle is characterized through a strongly varying power. Even if the maximum torque is used at the start from zero speed, the power demand is very low. The maximum power is only reached when the maximum torque is demanded at the maximum of the speed. The rated power corresponding to the maximum power will be used in the next section for the evaluation of the efficiency. It has the advantage to be clearly defined and represents the worst case of the driving mode for the efficiency.

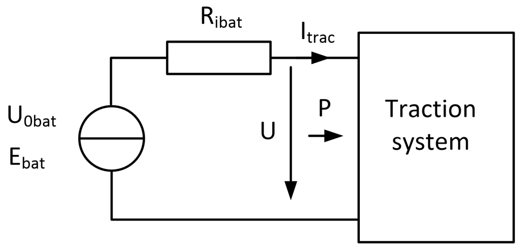


Fig. 14 Equivalent scheme for the driving mode

For the evaluation of the efficiency the tool of the Ragone representation is used again. When neglecting the self-discharge resistance the expression of the transferred energy (rel. 10) becomes

$$E_b(P) = P \cdot t_\infty = \frac{2RQ_0P}{U_0 - \sqrt{U_0^2 - 4RP}} \quad (19)$$

With the maximum value the power can reach

$$P_{\max} = U_0^2 / 4R \quad (20)$$

The Ragone plot in the dimensionless units can directly be used for the representation of the efficiency conditions of the driving mode as it can directly be used for any battery. The parameters of the battery (internal voltage, internal resistance and maximum power are entirely defining the locus on the Ragone plot.

The maximum power being

$$P_{\max} = U_0^2 / 4R = (387.7V)^2 / 4 \cdot 0.1003\Omega = 374.7kW \quad (21)$$

The maximum of the driving power calculated at the level of the battery

$$P_{\text{drive\_max\_batt}} = 150kW / 0.72 = 208.33kW \quad (22)$$

For the operating point (max) the dimensionless values become

$$p = 208.332kW / 374.7kW = 0.55 \quad (23)$$

$$e = \frac{1}{2} \cdot \frac{0.55}{1-\sqrt{1-0.55}} = 0.83 \quad (24)$$

These parameters are represented on the Ragone plot of Fig. 15

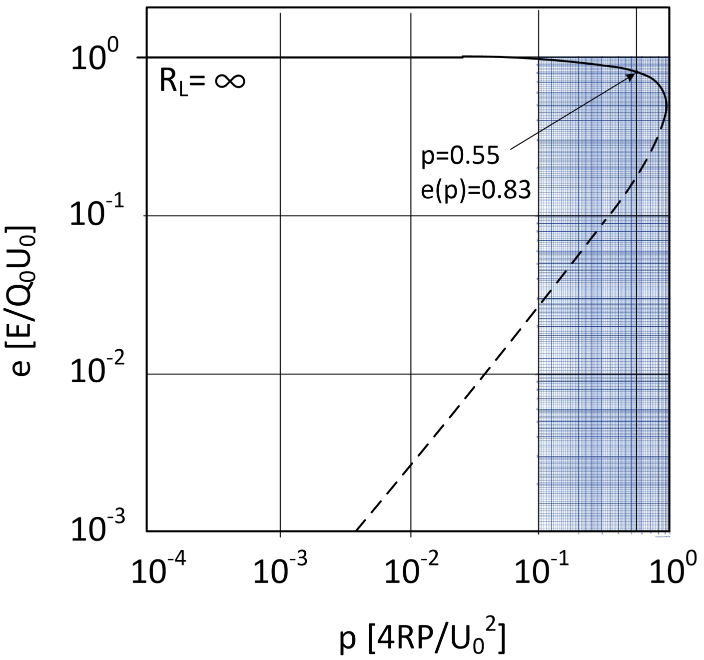


Fig. 15 Ragone representation of the driving mode

6.3 Overall efficiency

The overall efficiency of an electric vehicle is now calculated with the example of the VW ID3. This overall efficiency corresponds to the ration of the finally produced mechanical work at the wheels to the amount of energy delivered by the charging station
With the value of the charging efficiency at the highest allowed power of 120kW

$$\eta_{charge} = 0.925$$

With the drive efficiency at the highest propulsion power

$$\eta_{drive} = \eta_{disch\_batt} \cdot \eta_{prop} = 0.83 \cdot 0.72 = 0.597 \quad (25)$$

Leads to the overall value

$$\eta_{drive\_s-to-w} = \eta_{ch} \cdot \eta_{disch\_batt} \cdot \eta_{prop} = 0.925 \cdot 0.83 \cdot 0.72 = 0.55 \quad (26)$$

7. Conclusions

The typical behaviour of the charging and discharging processes of an energy storage device have been discussed in terms of the finally obtained efficiency. A global model is presented where the internal losses, the self-discharge losses and the auxiliaries power demand are considered. Cascaded transformations in a round trip storage as in a power-to power system based on hydrogen can lead to very low values of the efficiency.

The dependency between the energy amount recovered and the discharge power has been clearly shown. The method entitled The Theory of Ragone Plots has been used. Short charge and discharge times are related to strong current and cause high energy losses. In opposition to the discharge process where the power is limited by the battery typical behaviour and the fact that the discharge losses are covered by the battery energy itself, in the charging mode, the losses can be provided by the external charging infrastructure and the charging power is only limited by the admissible internal power dissipation and the elevation of the temperature.

References

[1] Rufer A., Energy Storage – Systems and Components, A. Rufer CRC Press, https://www.crcpress.com/Energy-Storage-Systems-and-Components/Rufer/p/book/9781138082625

[2] Karatza, D.; Konstantopoulos, C.; Chianese, S.; Diplas, S.; Svec, P.; Hristoforou, E.; Musmarra, D. Hydrogen production through water splitting at low temperature over Fe_3O_4 pellet: Effects of electric power, magnetic field, and temperature. *Fuel Processing Technol.* 2021, *211*, 106606. ISSN 0378-3820. https://doi.org/10.1016/j.fuproc.2020.106606.

[3] Wang, S., Lu, A. & Zhong, CJ. Hydrogen production from water electrolysis: role of catalysts. *Nano Convergence* **8**, 4 (2021). https://doi.org/10.1186/s40580-021-00254-x

[4] Recent progress in alkaline water electrolysis for hydrogen production and applications Kai Zeng, Dongke Zhang, Progress in Energy and Combustion Science 36 (2010) 307–326 (Elsevier)

[5] Eric Miller, Katie Randolph, David Peterson, The HydroGEN Consortium: Foundational early stage water-splitting research supporting diversification of the domestic hydrogen supply chain, Current Opinion in Electrochemistry
Volume 12, December 2018, Pages 196-201

[6] Zoller S, Koepf E, Nizamian D, Brendelberger S, Sizmann, Steinfel A, A solar tower fuel plant for the thermochemical production of kerosene from H 2 O and CO 2, Joule 6, 1606–1616, July 20, 2022

[7] Sivula Kevin, Towards Economically Feasible Direct Solar-to-Fuel Energy Conversion, Physical Chemistry Letters, American Chemical Society ACS, 2015, 6, 975-976.

[8] Christen T., Carlen M. W., Theory of Ragone plots, Journal of Power Sources, 91 (2000), p. 210-216.

[9] Energy storage Chapter 16 Springer Handbook on Power Systems Ed. Konstantin Papailiou, May 2021

[10] Rufer A., Energetic Properties of the (Fast) Charging and Driving of an Electric Vehicle – A Ragone Analysis, Facta Universitatis Electronics and Energetics June 2024

[11] Blanc Christian, Modeling of a vanadium redox flow battery electricity storage system, PhD Thesis EPFL Nr. 4227 2009, https://infoscience.epfl.ch/entities/publication/23e4c066-99f0-47a3-89e9-ae4d4425faf8

[12] Blanc, Christian, Rufer Alfred, Understanding the Vanadium Redox Flow Batteries chapter in Paths to Sustainable Energy Nathwani, Jatin, Ng, Artie, , ISBN 978-953-307-401-6, 2010, InTech, https://infoscience.epfl.ch/handle/20.500.14299/105918

[13] Devin Serpa, Tank-to-wheel efficiency, After Oil EV, http://www.afteroilev.com/Pub/EFF_Tank_to_Wheel.pdf

[14] Rufer A., Towards a Decarbonized Individual Mobility - Challenges and Solutions Journal of Physics Research and Applications, 2023, 7:4

[15] N. Wassiliadis, M. Steinsträter, M. Schreiber et al., Quantifying the state of the art of electric powertrains in battery electric vehicles: Range, efficiency, and lifetime from component to system level of the Volkswagen ID.3, eTransportation 12 (2022) 100167 (Elsevier).