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Review paper

ON THE EFFICIENCY OF ENERGY STORAGE SYSTEMS – THE INFLUENCE OF THE EXCHANGED POWER AND THE PENALTY OF THE AUXILIARIES

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Abstract. *Storage is an important domain of the energy sector, with its traditional, classical solutions for smaller and larger amounts of energy. Energy storage has become of higher importance in relation with the development of alternative energy sources, leading to the development of new technologies. The energy efficiency of the storage means is an important parameter, being often not considered in the conception and design of the applications. For the evaluation of the energetic performance of a storage device, a well-adapted tool has been proposed, namely "The Theory of Ragone Plots". This tool sets in evidence in what way the effectively recoverable energy amount of a device is depending on the power level of the charge/discharge process. Further, the taking into account of the power needed for the auxiliary equipment of a storage system like the circulation pumps of a flow battery, the vacuum pumps of a flywheel or the forced cooling of a battery can lead to a globally negative value of the efficiency.*

Key words: *Energy Storage, Efficiency.*

1. INTRODUCTION

High performance solutions for the accumulation of energy in order to cover the needs of the applications exist from longer time. Mechanical solutions invented by watchmakers or by manufacturers of film cameras are good examples of a pragmatic way to elaborate a solution to a specific problem. Higher amounts of energy have also been stored in the form of pumped water from a lower to a higher accumulation reservoir as it is widely spread in alpine regions.

Mobile as well as stationary applications have been the context of the development of a long list of different electrochemical accumulators, from the classical lead-acid batteries to the today's high-performance Lithium based metallic associations. All these solutions have mainly suffered from limited life cycle or other ageing phenomena like the loose of energy capacity or power availability.

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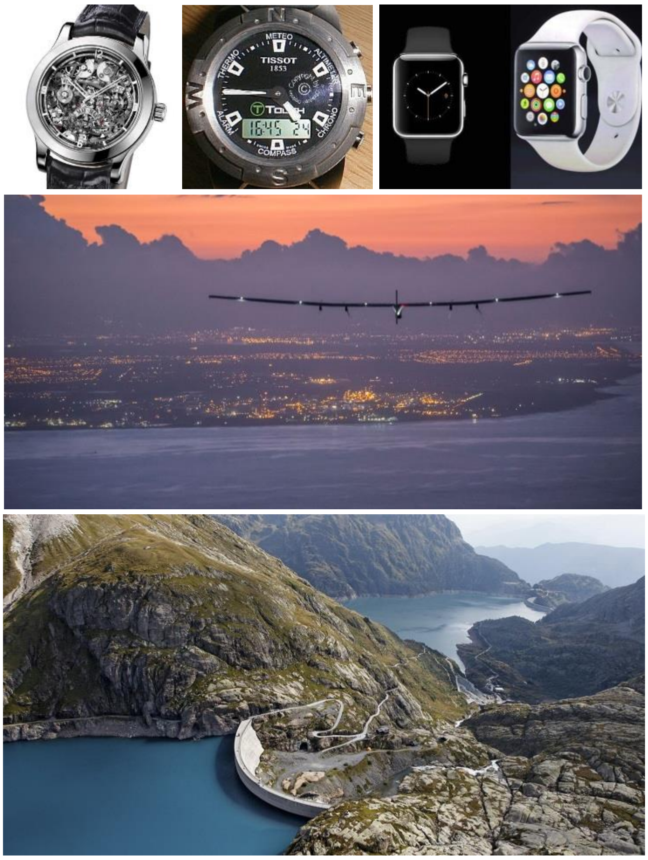
Other solutions have appeared along the years, as flywheels, compressed-air systems, superconductive magnets, but have never reached a breakthrough point, due to limited performance, high costs, or missing the adapted materials or infrastructure. Limited investment from the side of the industrial world is another reason for a stagnating evolution of storage alternatives, in the context of the largely available and cheap energy resources of the 20th century.

Environmental concern and limited fossil resources have been the triggers of the development of renewable sources, where the stochastic character of solutions as wind and solar generators has been a new motivation for the development of new and more performant energy storage solutions.

Today, the modern Li-ion accumulators can be seen as the most promising storage solutions for limited amount of energy at the level of several MWh, while other better adapted solutions as supercapacitors can solve the problem of the instantaneous power demand with less internal losses. Life cycle issues will remain a high motivation for the development of evolved solutions to the actual electrochemical battery, and totally different approaches as the chemical transformations into hydrogen or methane will be in the future the real alternative to pumped hydro power, allowing longer bridging through the seasons due to their much higher energy content [1], [2].



a)

b)

c)

Fig. 1 Examples of storage over a wide range of power and energy amount

Figure 1a illustrates the evolution seen in the domain of wrist watches, with at the right side a classical self-winding movement with an autonomy of 8 days. This former world record has been recently smashed up to 50 days [3]. The second object is an electronic watch with analogic and digital display and many new functions as altimeter, compass, etc. The autonomy of the battery powered watch is given as 24 months. The last watch is a connected device with an exploded number of new functions. Its autonomy felt down to around one or two tens of hours.

The second line (Fig. 1b) shows one of the most eccentric application of storage for electric mobility with the first airplane able to fly over night with energy collected from PV panels during the day (Solarimpulse, [4]).

The third line (Fig. 1c) represents a pumped storage plant in Switzerland (Nant-de-Drance, [5]). Its energy capacity is equal to 18’000 MWh, corresponding to an autonomy of 20 hours at the rated power of 900 MW.

The evolution of public grids from the conventional concept of centralized generation towards decentralized generation and the integration of as well the renewable sources as also decentralized storage facilities has been recently accelerated. The concept of adding storage systems in order to achieve the so-called day-to-night shift or in order to replace diesel generators has been called “The hybrid Power Plant” [6], (Fig. 2).

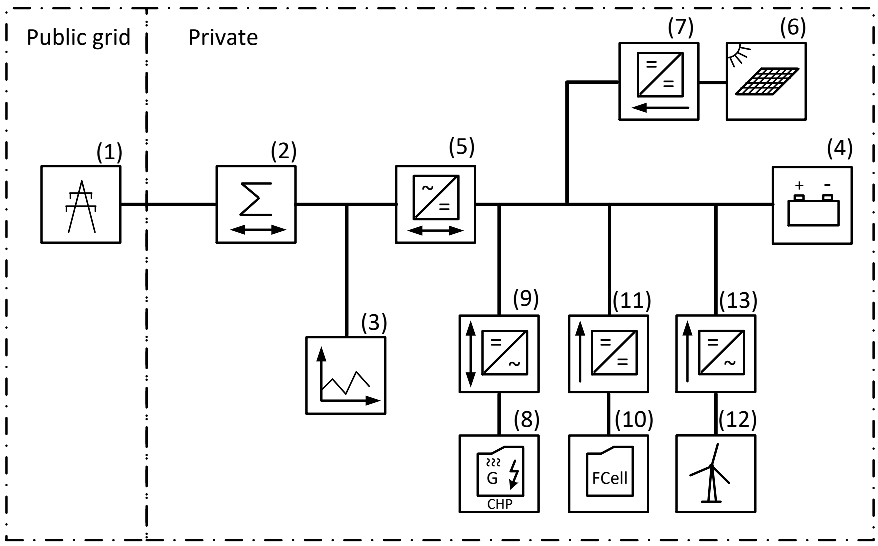


Fig. 2 The hybrid power plant

As already mentioned before, the different storage systems are covering a very large range of power and allow to store or release the energy over up to 10^3 hours as it is represented in Fig. 3. The diagram covers a very wide range of power, over six decades, from 1 kW to 1GW

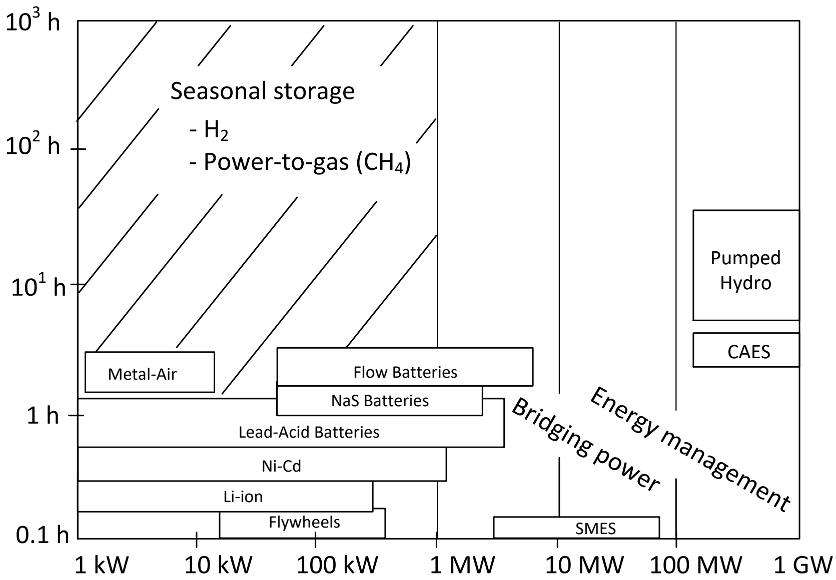


Fig. 3 Ratings of different storage systems

2. FOUR MAIN PARAMETERS FOR THE CHARACTERIZATION OF A STORAGE DEVICE

For the characterization of a storage device, and especially for mobile systems, not only the amount of stored energy is relevant but the power level of the charge and discharge processes must be defined. Thus, the energy density and the power density must be specified. More precisely, the volume and weight densities are generally specified as represented in Table 1.

Table I Four main parameters of energy storage devices

Parameter	*Symbol*	Unit
The *volume energy density*	e_v	[Wh/dm^3]
The *weight energy density*	e_m	[Wh/kg]
The *volume power density*	p_v	[W/dm^3]
The *power-to-weight ratio*	p_m	[W/kg]

Alternately to the specification of the amount of energy to be stored or to be recovered, together with the power level of the energy exchange, one can define the power and the time of needed power delivery. But the final result is equivalent.

On this base, engineers and manufacturers have proposed to use a simultaneous representation of the energy density and of the power density in the same diagram. Such a diagram is called the “Ragone chart”. Fig. 4 represents in the same Ragone chart the main parameters of different storage solutions [7].

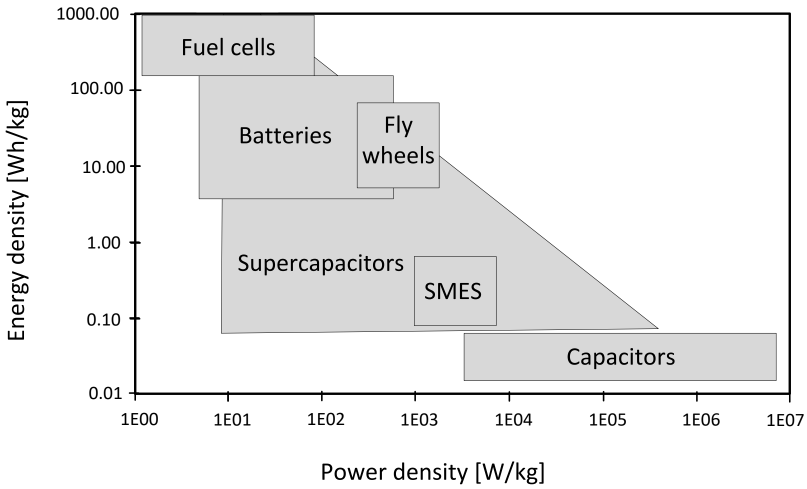


Fig. 4 The Ragone chart

3. Electrochemical Solutions Versus Systems from the Classical Physics

One other aspect of energy storage devices or systems is their life duration. Through specific parameters as life cycle or lifetime, the value of a given technology can be evaluated, also in terms of global costs of a given application. Fig. 5 shows the characteristics of several common technologies, together with the related energy efficiency. From this figure, one can see that classical as well as modern batteries show good to very good energy efficiencies. But they suffer from limited life cycles. The main reason is the ageing phenomena related to electrochemical processes with ion migrations and transformations of the molecular structures. The storage technologies based on electrochemical transformations are located over the range of only several hundreds to several thousands of cycles, what is a limiting factor in the domain of applications to Renewable Energy Sources. On the right side of Figure 5, beyond the order of magnitude of ten thousand cycles, technologies with higher numbers of possible cycles are represented. They generally belong to the category of solutions based on reversible physics. In this category, the term of *macroscopic energy* of a system is used and the amount of accumulated energy in the system is related to its movement and to the external effects as gravity, magnetism or electricity. More explicitly the category includes the classical hydraulic pumped storage, flywheels, superconductive magnetic energy storage, supercapacitors or compressed air energy storage.

Even if by these systems the number of possible cycles is several orders of magnitude higher than for electrochemical technologies, the system components are subject to ageing phenomena as metal wear, friction and ageing of bearings or alteration of insulations. Generally, the indicated lifetime of such systems includes revisions or replacement of sensitive sub-components.

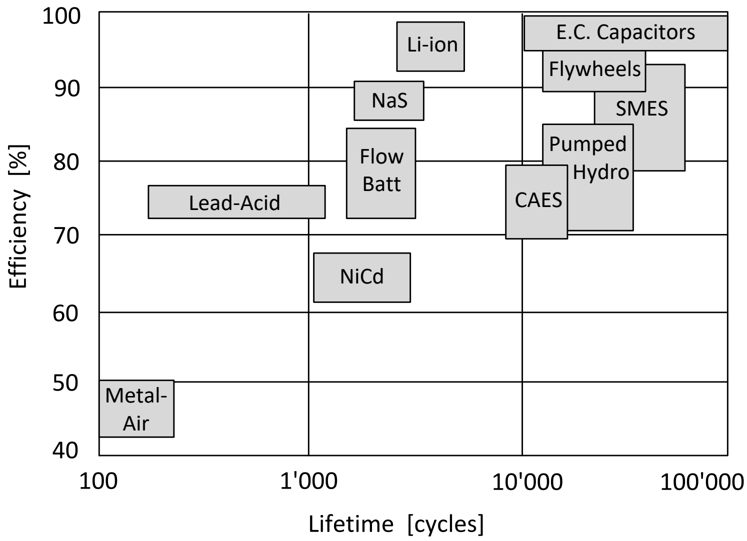


Fig. 5 Efficiency and lifetime of energy storage solutions

Recently, the category of storage systems based on physics has been completed by an original proposal to realize “dry gravitational storage systems”. In such installations, the stored energy amount is obtained from a stack of blocks of concrete. The blocks are moved up-and-down with a multiple arm crane system [8], [9]. Figure 6 shows the so-called Energy Vault demonstration system currently under construction.

Fig. 6 The Energy Vault system, a Dry Gravitational Storage System

4. A GENERAL MODEL FOR THE EFFICIENCY

The quality of a storage system is quantified through its energy efficiency, taking 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 7 shows the energy flow of a storage system where all the listed effects are represented. 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. In order to evaluate the different penalties, the next section will briefly introduce the “Theory of Ragone Plots”.

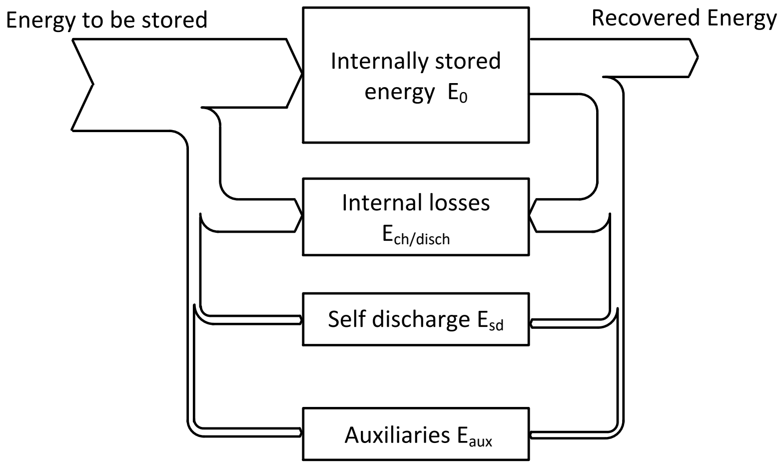


Fig. 7 Energy flow to and from a storage system

5. THE THEORY OF RAGONE PLOTS

As already explained in the previous section, the energy efficiency of a storage device is related to the different losses. Charging and discharging losses as well as the self-discharge losses influence directly the round-trip efficiency. As a consequence the amount of energy which can really be recovered from a fully charged storage device has to be defined in dependency of the instantaneous power of the energy transfer. This principle of interdependency between the energy density and the power density has been described under the name of «The theory of Ragone plots» [11].

In this reference, a general circuit is associated with Ragone plots (Fig. 8). The energy storage device (ESD) feeds a load with constant power P. The ESD contains elements for energy storage. Due to constant power, energy supply occurs only for a finite time $t_{inf}(P)$. The energy amount E available for the load in dependency of the power P defines a Ragone plot.

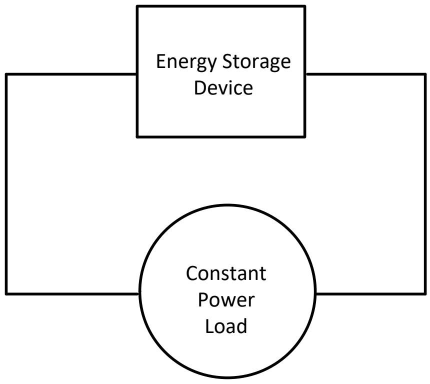


Fig. 8 General circuit associated with Ragone plots (Adapted from [11])

Consider the general circuit of Fig. 8. For example, the ESD may consist of a voltage source, V(Q), depending on the stored charge Q, an internal resistor R, and an internal inductance L. Note that this ESD can describe many kinds of electric power sources.

The ESD is connected to a load which draws a constant power $P \geq 0$. Such a load can be realized with an electronically controlled power converter feeding an external user. The current I and voltage U at the load are then related nonlinearly by U = P/I. Provided reasonable initial conditions

$$Q(0) = Q_0 \quad \text{and} \quad \dot{Q}(0) = \dot{Q}_0$$

are given, the electrical dynamics is governed by the following ordinary differential equation:

$$L\ddot{Q} + R\dot{Q} + V(Q) = -\frac{P}{\dot{Q}} \tag{1}$$

where the dot indicates differentiation with respect to time.

This equation applies not only to electrical ESD but covers many kinds of physical systems (mechanical, hydraulic, etc.). Without making reference to a specific physical interpretation of rel. (1), the Ragone curve can be defined as follows. At time t = 0, the device contains the stored energy

$$E_0 = L\dot{Q}_0^2 / 2 + W(Q_0) \tag{2}$$

For t > 0, the load draws a constant power P such that Q(t) satisfies the relation (1). It is clear that for finite E_0 and P, the ESD is able to supply this power only for a finite time, say t_{inf} (P). A criterion is given either by when the storage device is cleared or when the ESD is no longer able to deliver the required amount of power. Since the power is time independent, the available energy is

$$E(P) = P \cdot t_{\inf}(P) \tag{3}$$

The curve E(P) versus P corresponds to the Ragone plot.

5.1. The Ragone plot of a battery

In this section, the particular case of an ideal battery is studied. First, and regarding the model leading to the rel. (1), we assume the condition $L = 0$. Then, the ideal battery with a capacity of Q_0 is characterized by a constant cell voltage $V = U_0$ if $Q_0 \geq Q > 0$ and $V = 0$ if $Q = 0$. In a first step, the leakage resistor R_L is neglected.

Rel. (1) reads:

$$P = U \cdot I = (U_0 - RI)I$$

where U is the terminal voltage and $I = \dot{Q}$ is the current.

The solutions of the quadratic equation are

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

At the limit $P \to 0$, the two branches correspond to a discharge current

$$I_{+} \to U_0 / R \quad \text{and} \quad I_{-} \to 0 .$$

For the ideal battery, the constant power sink can also be parametrized by a constant load resistance R_{load}.

The two limits belong then to $R_{load} \to 0$ (short circuit) and $R_{load} \to \infty$ (open circuit) respectively.

Clearly, in the context of the Ragone plot, we are interested in the latter limit, such that we have to take the branch with the minus sign, $I \equiv I_{-}$ in eq. (2).

Now the battery is empty at time $t_{inf} = Q_0 / I$, where the initial charge Q_0 is related to the initial energy $E_0 = Q_0 U_0$. It is now easy to include the presence of an ohmic leakage current into the discussion. The leakage resistance R_L increases the discharge current I by U_0/R_L.

The energy being available for the load becomes:

$$E_b(P) = P \cdot t_{\infty} = \frac{2RQ_0P}{U_0 - \sqrt{U_0^2 - 4RP + 2U_0R/R_L}} \tag{5}$$

Equation (5) corresponds to the Ragone curve of the ideal battery. In the presence of leakage, $E_b(0) = 0$. For the extracted energy, there exists a maximum at $P = U_0^2 / \sqrt{2RR_L}$

Without leakage $R / R_L \to 0$, the maximum energy is available for vanishing low power $E_b(P \to 0) = E_0$. From eq. (5), one concludes that there is a maximum power, $P_{\max} = U_0^2 / 4R$ associated with an energy $E_0/2$ (a small correction due to leakage is neglected).

This point is the endpoint of the Ragone curve of the ideal battery, where only half of the energy is available while the other half is lost at the internal resistance.

Finally, the expression of the Ragone plot is given in the dimensionless units using $e_b = E_b / Q_0U_0$ and $p = 4RP / U_0^2$

$$e_b(p) = \frac{1}{2} \frac{p}{(1 - \sqrt{1-p} + 2R / R_L)} \tag{6}$$

Ragone curves according eq. (6) with and without leakage are shown in Fig. 9 for the ideal battery. The branch belonging to I_+ is plotted by the dashed curve.

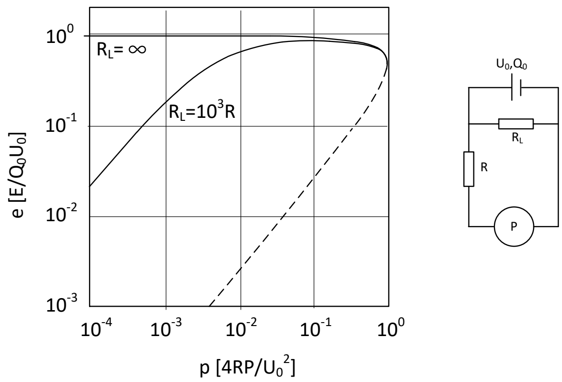


Fig. 9 Ragone curve of the ideal battery (Adapted from [11])

5.2 The case of superconductive magnetic energy storage SMES

The Ragone curves of superconductive magnet energy storage systems are also described in details in [5]. Figure 10 gives the normalized curves for inductive energy storage devices with Coulomb (C), Stokes (S), and Newton (N) friction. The dashed double-dotted curve corresponds to a SMES with an ohmic bypass ($4R/R_b$ = 0.001). This resistance R_b is used for the modelling of the losses of all freewheeling paths, with a dominant contribution of the freewheeling elements of the power electronic converter.

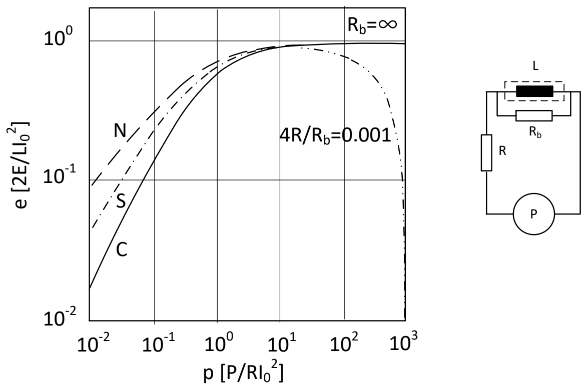


Fig. 10 Normalized Ragone curves for the inductive ESD (Adapted from [11]).

6. THE MRR (MODIFIED RAGONE REPRESENTATION)

A slightly different model for the representation of the relationship between the really recoverable energy amount of a storage device and the power level of the exchange has been proposed in [12]. This MRR (Modified Ragone Representation) is based on a simple equivalent circuit which can be used for example for a battery. This equivalent circuit includes a series resistor for the model of the charging and discharging losses, and a parallel resistor for the model of the self-discharge (Fig. 11).

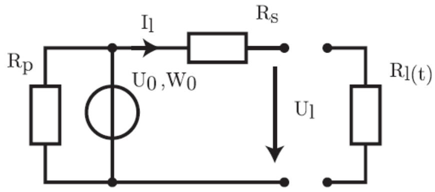


Fig. 11 Equivalent scheme for the MRR

The energy that can be recovered from the storage device is represented in function of the transfer power P (logarithmic scale, Fig. 12). A too small power in the range of the self-discharge losses results into a nearly zero energy to be recovered (left ends of the curves in Fig. 12). At the right end of the MRR curves, the effect of a too high transfer power results in a similar situation of zero recovery due to the high internal losses.

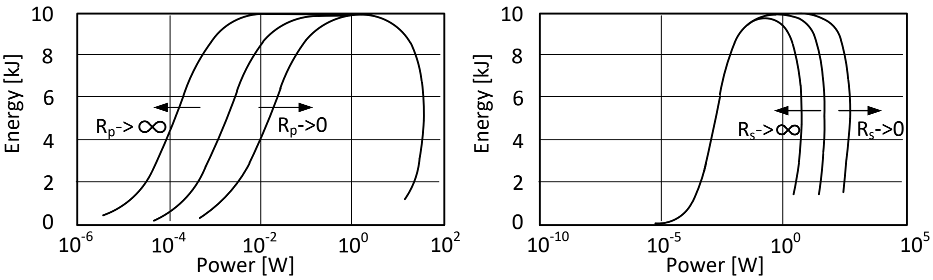


Fig. 12 The MRR (Modified Ragone Representation).

7. From a Positive to a Negative Efficiency

In section 3, 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. 13 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.

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

$$\eta_{roundtrip} = \frac{(P_{stackdisch} - P_{mech})}{(P_{stackch} + P_{mech})} \qquad (7)$$

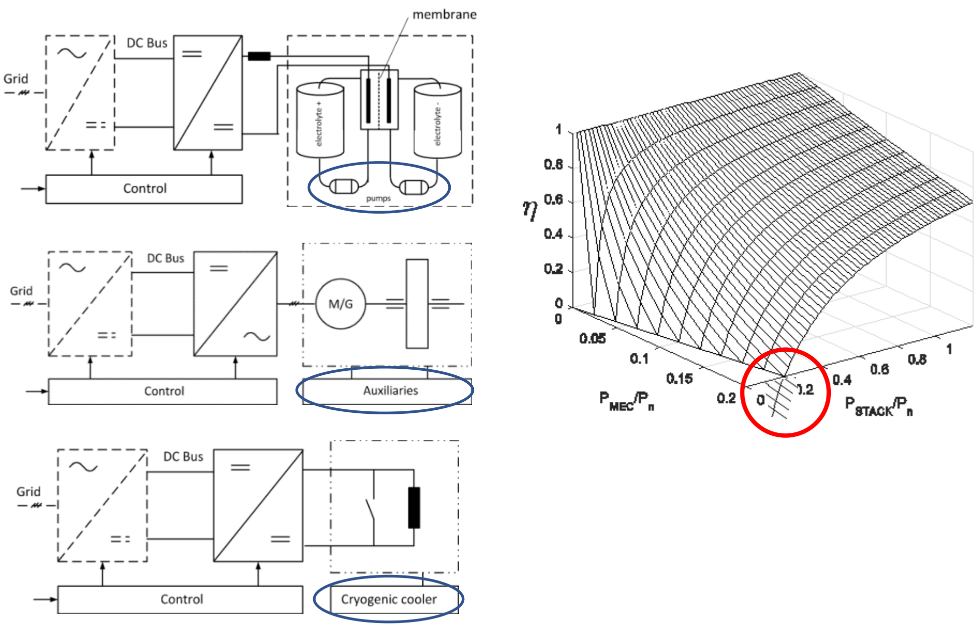


Fig. 13 Effect of the auxiliaries on the efficiency

From relation (7), 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. 13 (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. 13, 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.

8. Conclusions

Energy storage has been and will be in the future a component with growing importance in the wide field of powered systems. A broad range of power and energy capacity is characterizing the storage components.

A general model for the efficiency and new tools have been described where the real amount of recoverable energy in dependency of the power level of the exchange can be calculated. In the context of alternative and renewable energy supplies, new storage supports are proposed as flow batteries, flywheels or even superconducting magnetic components. As for all storage devices, the energy efficiency must be quantified and the operation boundaries for a reasonable global performance must be defined.

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