Chargers and Charging Infrastructure
(Course code: EV-355)

Introduction to Energy Storage

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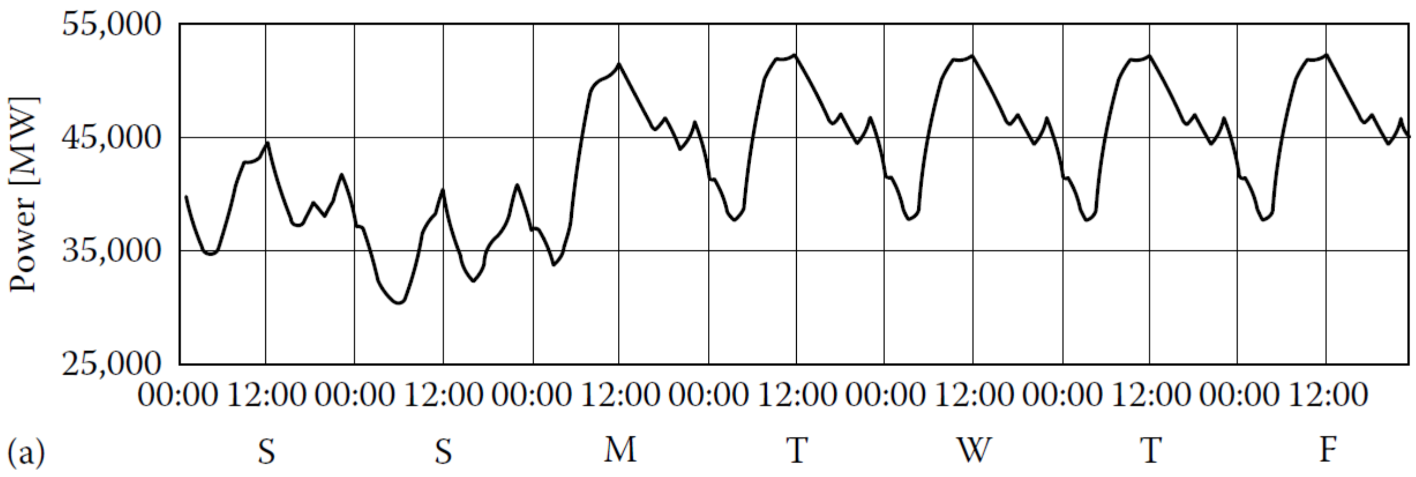
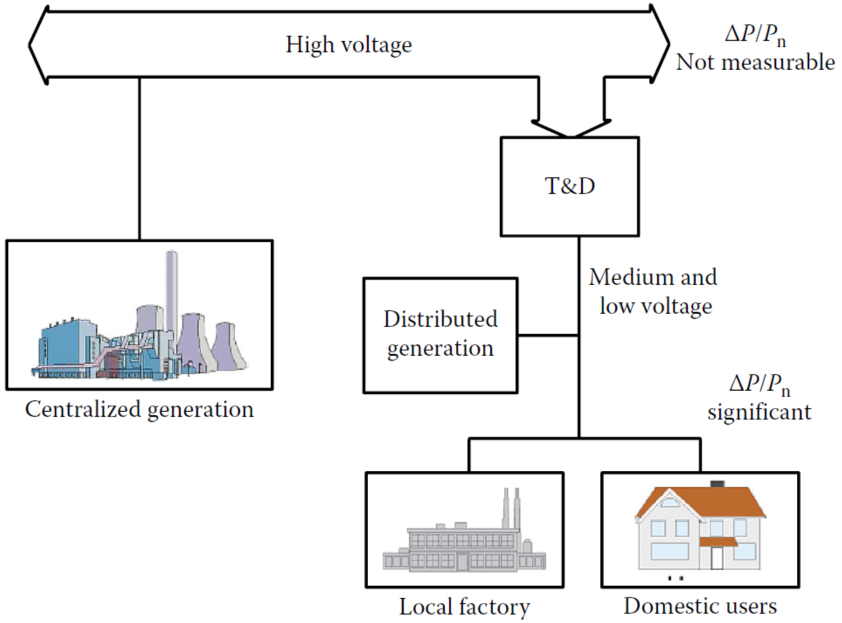
Need of Energy Storage Systems

❖ Increasing the use of energy storage can be observed due to, the use of storage technology to solve the problem of availability of sources (day-to-night shift for photovoltaic plants as a first example, or the bridging of lack of production of fluctuating sources).

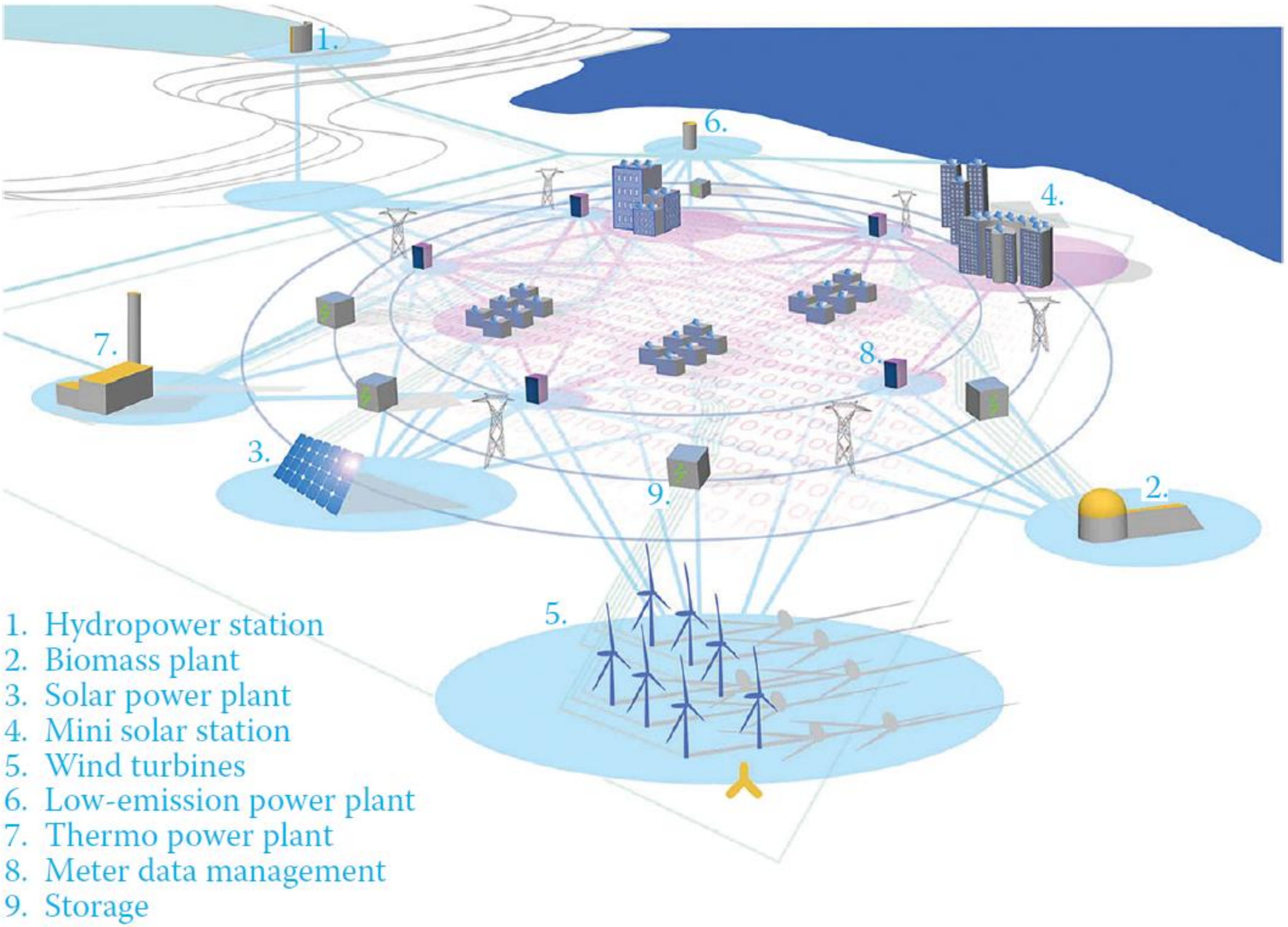


Daily variations of the power demand profile over a week

- ❖ When the local generation cannot follow the strong and fast demand. Examples: In the case of a "microturbine" the fast increase of load must respect some minimum time constant.
- ❖ In the case of the use of "fuel cells," the design of these systems for the maximum peak power can lead to unacceptable costs.
- ❖ This concerns the power matching between decentralized generators and their loads nearby that can generate significant and fast variations of the local power demand.



Power fluctuations ($\Delta P/P_n$) in centralized and decentralized power generation systems.



Centralized utility of today to distributed utility of tomorrow

Smart Grid is an Electrical Grid with Automation, Communication and IT systems that can monitor power flows from points of generation to points of consumption (even down to appliances level) and control the power flow or curtail the load to match generation in real time or near real time.

GENERAL DEFINITIONS

ENERGY:

The most convenient way to define energy is to use its relationship to the integral of the exchanged power for a time duration:

$$E=\int_{t_1}^{t_2} P(t)dt$$

For a system with a rotating mass, the term for the kinetic energy becomes

$$KE_{rot} = J\frac{\omega^2}{2}$$

Where,

J is the moment of inertia.

ω is the angular velocity.

- A simple definition of the total energy is given by the sum of the internal energy U, the kinetic energy KE, and the potential energy PE, leading to the expression of relation-

$$E = U + KE + PE = U + m\frac{V^2}{2} + \mathrm{mgz}$$

Where,
'm' is the mass.
'V' is the velocity of the mass.
'g' is the gravitational acceleration.
'z' is the height of the mass of centre from the reference point.

- Magnetic and electric effects can play a major role in the energy of given systems like inductors or capacitors. These amounts are considered as macroscopic energy and can be calculated as,

$$E = E_{mag} + E_{el} = \frac{1}{2}LI^2 + \frac{1}{2}CV^2$$

Where,
L is inductance.
C is capacitance.

POWER:

Power can be defined as the “energy flow rate” to or from a given system:

$$P(t) = \frac{dE}{dt}$$

Where,

P (power) is expressed in Watt [W], [kW], [MW],

E (energy) is expressed in Joules [J], [kWh],

t (time) in seconds [s], hours [h].

LOSSES:

❖ Charge and Discharge Losses

One can suppose the charge and discharge losses being of the form

$$P_{ch} = \propto P^2$$

❖ Total Losses

Considering one operating cycle of the storage device that is characterized by one specific power profile P(t) and by one state of energy SoE(t), the total losses P_{loss} are equal to the sum of the charge/discharge losses added to the self-discharge losses:

$$P_{loss} = \propto P^2 + P_o(SoE(t))$$

❖ SoE

Further, the dissipated energy E_{loss} over one complete cycle can be calculated as,

$$E_{loss\_cyc} = \int \{P_{loss} = \ \propto P^2 + P_o(SOE(t))\}\mathrm{dt}$$

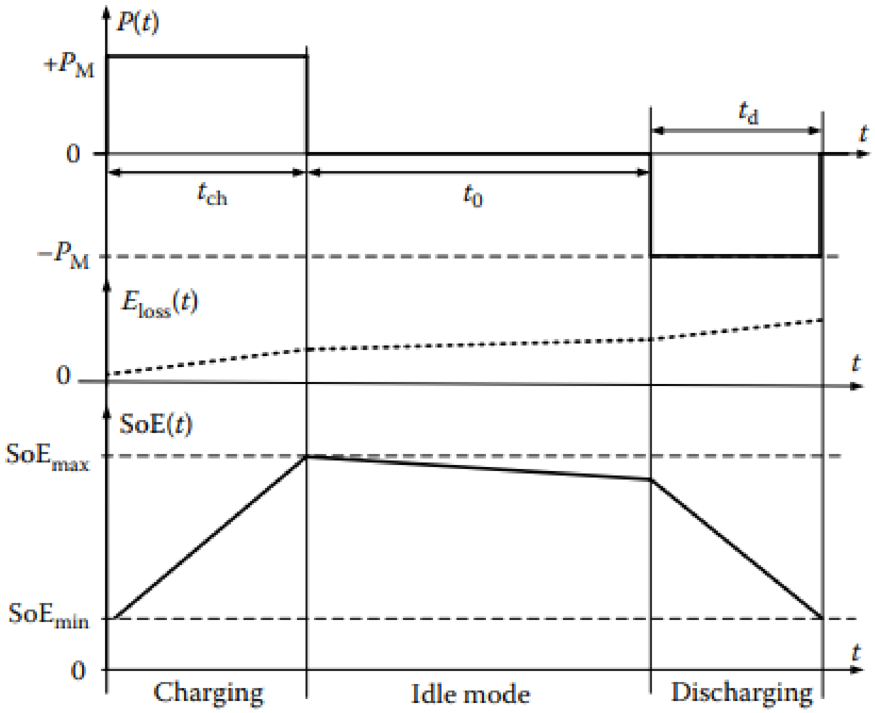
By convention, the energy storage device is defined as an energy sink, and consequently, the power P(t) is positive during the charge phase and negative during the discharge phase. The profile of the SoE is given by

$$SoE(t) = SOE(t_o) + \frac{\int [P(t) - P_{loss}(t)]dt}{E_{stored}}$$

❖ Round-trip efficiency

Round-trip efficiency η_c is the ratio of the recovered energy E_d during the discharge to the spent energy E_{ch} for the charging, calculated as a mean value over one charging/discharging cycle. Such a cycle can be chosen arbitrarily.

SoE after discharge must be identical to the SoE before the charging process.



Charging and discharging curve

Numerical Problem

Q1. An electric vehicle (EV) battery undergoes a charge and discharge cycle. During charging, the battery is supplied with 10 kWh of energy. However, due to losses in the charging process, only 9 kWh of energy is effectively stored. During the discharge cycle, 8.5 kWh of energy is delivered to the motor. Calculate the round-trip efficiency of the battery and create a MATLAB code to simulate this process and compute the efficiency and plot the curve for Charging and Discharging Curves with Round-Trip Efficiency?

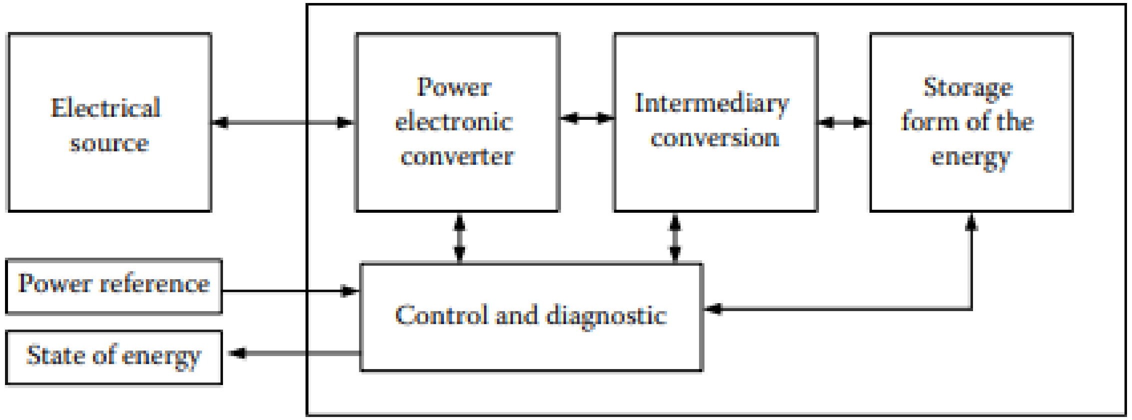
Storage Form of Energy

The storage forms of energy can be various:

- ❖ The potential energy associated with the earth's gravity when one mass is moved from one altitude to another (e.g., **water in a pumped-storage plant**).
- ❖ The kinetic energy of a mechanical system in rotation (**flywheels**).
- ❖ The pressure of a compressible fluid (**compressed air).**
- ❖ Covalent bonds of given molecules (**electrochemicals**).
- ❖ Electric or magnetic state variables (**electrical field, magnetic field, capacitors, superconducting inductors).**

Intermediary Conversion

- The interface between the storage form unit and the electrical level (output of the power electronic converter) may need the so-called intermediary conversion, shown in Figure.
- The intermediary conversion can vary. For example, it includes the electric motor/generator and the hydraulic pump/turbine in a pump-storage plant or can simply be the electric driving machine of a flywheel.



Energy Storage System

Battery Based Energy Storage: Parameters

Capacity:

- ❖ C is the quantity of electricity to be recovered from a storage. It is generally expressed in Ah and corresponds to the integral of the current:

$$E = \int_0^t i(t)dt$$

DoD (Depth of Discharge):

- ❖ DoD is the indication of the quantity of electricity already extracted from an storage related to its maximum capacity:

$$DoD = \frac{\int_0^1 i_{dis}(t)dt}{capacity}$$

SoC (State of Charge)

- SoC is an indication of the remaining quantity of electricity available from a storage, related to its maximum available capacity:

$$\mathrm{SoC} = \frac{Amount\ of\ remaining\ charge}{Practical\ capacity\ of\ an\ acumulator}$$

$$SoC = \frac{capacity - \int_0^1 i_{dis}(t)dt}{capacity}$$

Numerical Problem

Q2. A 12V, 100Ah lithium-ion battery used in a solar energy system. The battery was fully charged initially (SoC = 100%). After running for 5 hours, the battery's remaining capacity is 60Ah.

1. Find the Depth of Discharge (DoD) after 5 hours.
2. Determine the battery's State of Charge (SoC) after 5 hours.
3. If the load on the battery was 500W during those 5 hours, calculate the average current drawn by the load.
4. If the same load continues, how long will the battery last before it is fully discharged?

Battery Pack: Types of Batteries

- Battery packs are the heart of Battery Electric Vehicles (BEVs), serving as the primary energy storage system. The type of battery used directly impacts the vehicle's performance, range, charging time, and overall efficiency.

Below are the most used battery types in BEVs

- Lithium-Ion Batteries (Li-Ion)
- Solid-State Batteries
- Nickel-Metal Hydride Batteries (NiMH)
- Other Emerging Battery Technologies

Oldest Rechargeable Battery Technology: Invented by Gaston Planté in 1859, making it the first rechargeable battery.

- ❖ **Description:** Mature technology, low cost.
- ❖ **Common Use:** Widely used in automotive applications (starting, lighting, and ignition systems), uninterruptible power supplies (UPS), and backup power for telecommunications.
- ❖ **Advantages:** Reliable, high surge currents.
- ❖ **Disadvantages:** Lower energy density, shorter lifespan.

Lithium-Ion Batteries

Overview: The most widely used battery type in BEVs due to their high energy density, lightweight, and long lifespan. Typically involves lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), or nickel manganese cobalt (NMC) chemistry.

- **Modern Rechargeable Battery Technology:** First commercialized in the 1990s by Sony, now one of the most widely used rechargeable batteries.
- **Description:** Modern, widely used in consumer electronics and EVs.
- **Common Use**: Used in various applications, from smartphones and laptops to electric vehicles (EVs), medical devices, and renewable energy storage.

Advantages

- **High Energy Density:** Offers more energy storage per unit weight, translating to longer driving ranges.
- **Efficiency:** High charge/discharge efficiency, making them ideal for regenerative braking systems.
- **Longevity:** Can endure many charge cycles, typically 1,000 to 2,000 cycles before significant degradation.

Disadvantages: Higher cost, thermal stability issues.

Solid-State Batteries

- **Overview:** An emerging technology that uses solid electrolytes instead of the liquid electrolytes found in traditional Li-Ion batteries.
- **Chemistry:** Typically uses Lithium metal or Lithium-Sulphur chemical with a solid electrolyte.

Advantages

- **Higher Energy Density:** Can potentially offer up to 2-3 times the energy density of current Li-Ion batteries.
- **Safety:** Reduced risk of fire and thermal runaway due to the absence of flammable liquid electrolytes.
- **Longevity:** Promises longer battery life and faster charging times.

Nickel-Cadmium (NiCd) Batteries

- **One of the Oldest Rechargeable Technologies:** First developed in 1899 by Waldemar Jungner, Nickel-Cadmium (Ni-Cd) batteries were widely used before being overtaken by newer technologies like lithium-ion.

- **Description:** Used in applications requiring high discharge rates.
- **Common Use:** Used in power tools, emergency lighting, aviation, and some portable electronics, though now largely replaced by nickel-metal hydride (NiMH) and lithium-ion.
- **Advantages:** Good performance at low temperatures, robust.
- **Disadvantages:** Memory effect, toxic cadmium.

Nickel-Metal Hydride (NiMH) Batteries

- **Overview:** Previously, it was more common in hybrid electric vehicles (HEVs) and early BEVs, but it is now largely replaced by Li-Ion batteries. In 1989, Nickel-Metal Hydride (NiMH) Batteries were introduced, offering higher capacity and reduced environmental impact compared to nickel-cadmium (NiCd) batteries.
- **Description:** Common in hybrid vehicles and some consumer electronics.
- **Chemistry:** Uses nickel oxide hydroxide and a hydrogen-absorbing alloy as the positive and negative electrodes, respectively.

Advantages

- **Durability:** Known for their robustness and ability to withstand harsh conditions.
- **Safety:** Lower risk of thermal runaway compared to early Li-Ion designs.
- **Cost:** Generally, less expensive than Li-Ion batteries.

Disadvantages: More expensive than NiCd, lower energy density than Li-Ion.

Other Emerging Battery Technologies

Lithium-Sulphur (Li-S) Batteries:

- **Overview:** Promises higher energy density and lower cost by using sulphur as a cathode material.
- **Advantages:** Lightweight and potentially cheaper.
- **Challenges:** Limited cycle life and ongoing research to address this issue.

Lithium-Iron Phosphate (LFP) Batteries:

- **Overview:** A type of Li-Ion battery known for its safety and longevity.
- **Advantages:** Higher thermal stability, longer cycle life, and lower cost.
- **Challenges:** Lower energy density compared to nickel manganese cobalt (NMC) or lithium cobalt oxide (LCO) batteries.

Zinc-Air Batteries:

- **Overview:** Uses zinc and oxygen to produce electricity.
- **Advantages:** Extremely high energy density and potentially lower cost.
- **Challenges:** Issues with recharging and durability still need to be resolved.

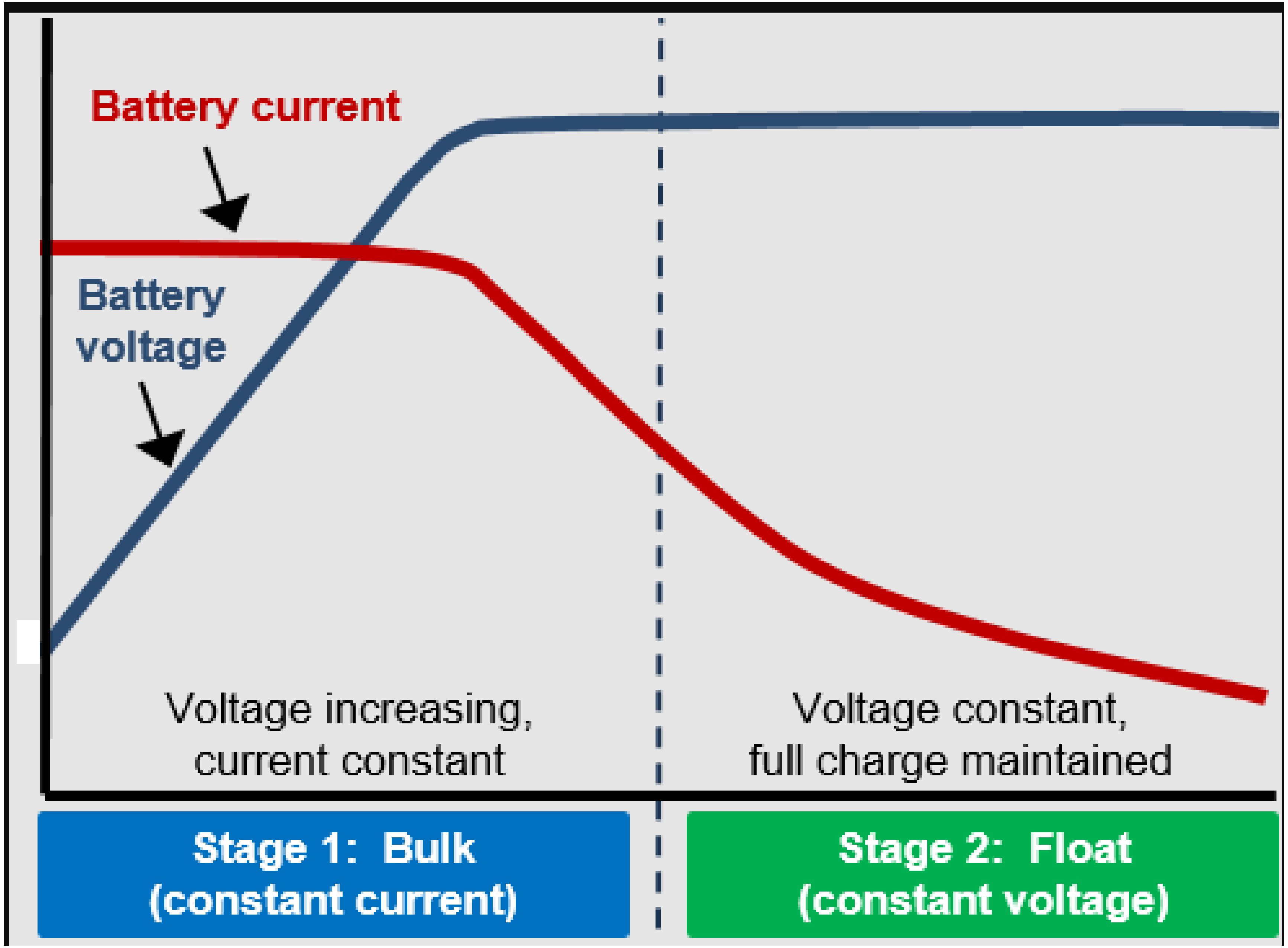
Sodium-Ion Batteries:

- **Overview:** A promising alternative to lithium-based batteries, using more abundant sodium.
- **Advantages:** Cost-effective and environmentally friendly.
- **Challenges:** Lower energy density and still under development for BEV applications.

Charging and Discharging Cycles

1. Charging Cycle:

- **Definition:** The process of adding electrical energy to a battery to increase its charge. This involves supplying current to the battery until it reaches its full charge capacity.
- **Methods:** Batteries can be charged using various methods, including constant current (CC) charging, constant voltage (CV) charging, or a combination of both. The method used depends on the battery type and manufacturer recommendations.

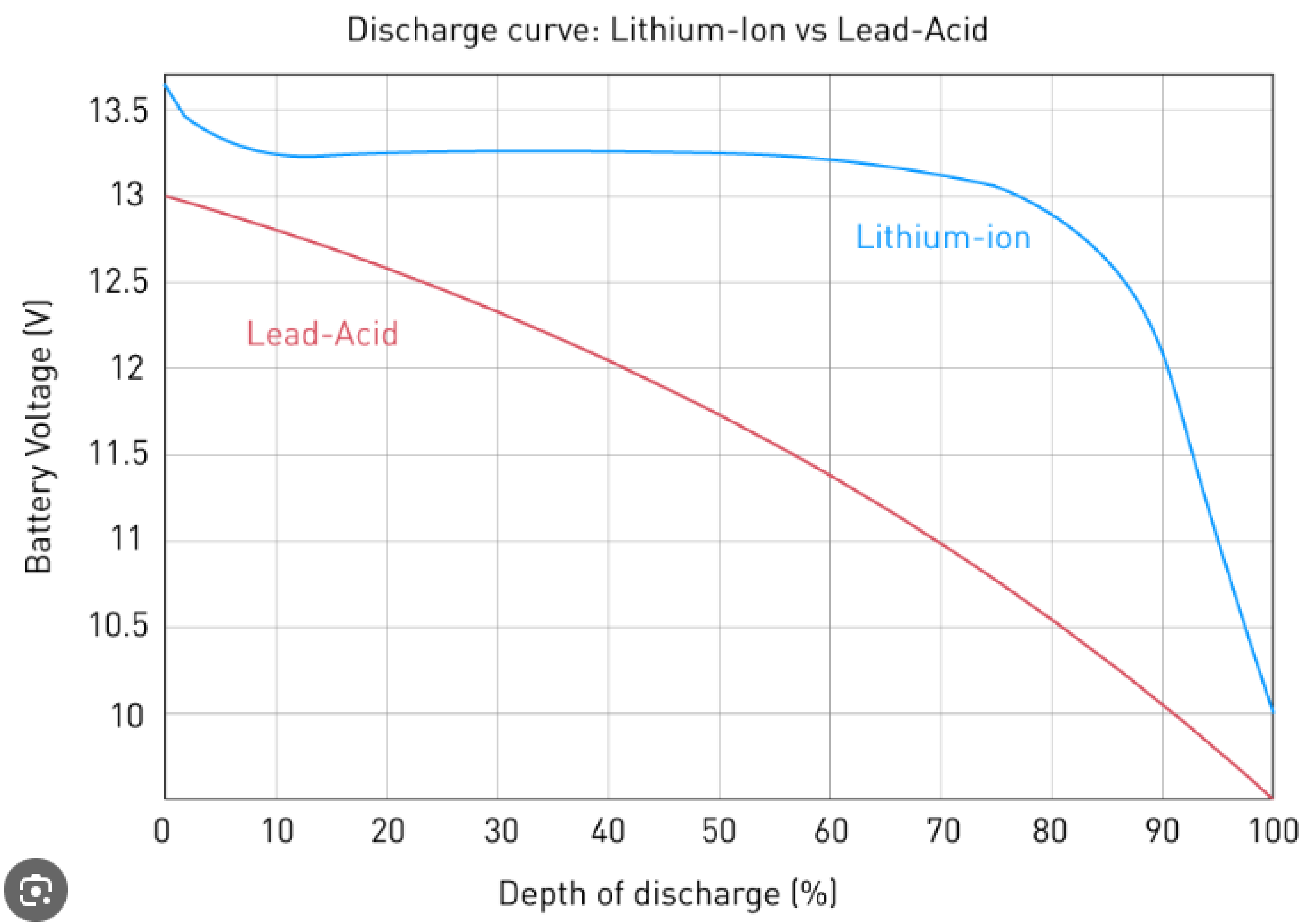


Battery charging profile.

2. Discharging Cycle:

- **Definition:** The process of drawing electrical energy from a battery to power a device or perform work. This involves the battery supplying current until its charge drops to a predefined level, often termed the cut-off voltage.

- **Methods:** Discharging can be constant current, constant power, or a more complex profile depending on the application and battery design.

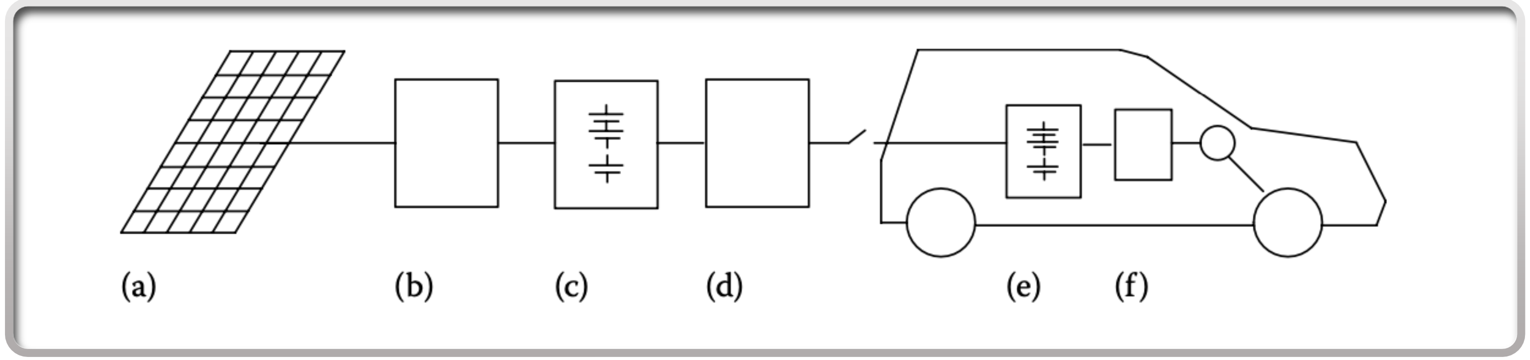


Battery discharging profile.

NORMAL AND FAST CHARGE OF BATTERIES IN EVS

Modern batteries claim high C-rates up to factors 8 (short-term 15), which could make a possible fast charge in electric vehicle (EV) applications. A system is studied where the energy can be collected from PV panels and restored during the day. The energy transfer from the local battery to the vehicle battery at the end of the day can then be realized in a longer or shorter time.

Even if no PV panels are used, the pre-charge of the local battery is done from grid electricity, and the role of that local battery will be to serve as a buffer, avoiding the high-power solicitation from the grid during the fast charge (high power) of the EV battery.



EV charging from RES (PV)
(a) PV panels, (b) MPPT converter, (c) local battery, (d) DC–DC converter, (e) car battery, and (f) propulsion system.

Technical Parameters

1: Local Battery

- The local battery is realized with 135 elements of 3.7 V and 0.7 mΩ internal resistance. The no-load voltage of the local battery is 500 V.
- The local battery energy capacity is equal to 25 kWh.
- From the nominal capacity of the elements (50 Ah) the rated current is defined as 50 A, corresponding to a C-factor equal to 1 (under C = 1 conditions, the charging time is equal to 1 h).

2: Car Battery

- The car battery is realized with 108 elements of 3.7 V and 0.7 mΩ internal resistance (identical elements as for the local battery).
- The no-load voltage of the car battery is 400 V.

Technical Parameters

3: Converter Losses

- The converter losses are calculated through the conduction loss of the silicon devices with a forward voltage of the devices (transistors and diodes) equal to 1.5 V.

4: PV Panels

- The PV panel surface is designed according to the charging time of the local battery within 7 h, from SoC 20% to full charge SoC 100%.
- The required panel surface must be calculated for the following conditions:

Irradiance (ε) = 800 W/m2 (mean value) η_{cells} = 10%

The charging system with buck and boost converters is affected by power losses in the following elements (simplified estimation):

❖ Ohmic losses in the inductors.

❖ Conduction losses in the power semiconductors of the boost and buck converters.

❖ Ohmic losses in the battery.

For the estimation of the losses, it is considered that the PV panels are operated at a voltage level corresponding approximately to the voltage level of the local battery. Therefore, one can suppose the input current of the boost converter is identical to the output current of the buck converter.

Structure of the System, Converters, and Cascaded Conversions

The electric scheme of the system with the different converters should be drawn.

Slow charge (7 h)

The current in both the PV panels and the local battery should be “non-discontinuous.” It is smoothed with inductors:

L = 9.15 mH, R_L = 0.2 Ω

Fast energy transfer from the local battery to the car battery (C_{rate}= 8).

In order to reduce costs, there is only one converter for both batteries (step- down converter). The current in the car battery is smoothed with an inductor: L = 9.15 mH, R_L = 0.32 mΩ

Calculation of Energy efficiency

A: Calculate the energy efficiency of a charge from the PV panels (slow charge, 7 h).

- ❖ For this case (a), there is a step-up converter cascaded with a step-down converter. Between the two converters, there is a constant DC voltage link based on a buffer capacitor.
- ❖ The energy efficiency is calculated based on the different power losses (converters, smoothing inductors, internal losses of the battery).

B: Calculate the energy efficiency of a charge of the car battery (from the local battery, case b) for different charging times (using the C-rates of 2, 4, 6, 8, 10, 12).

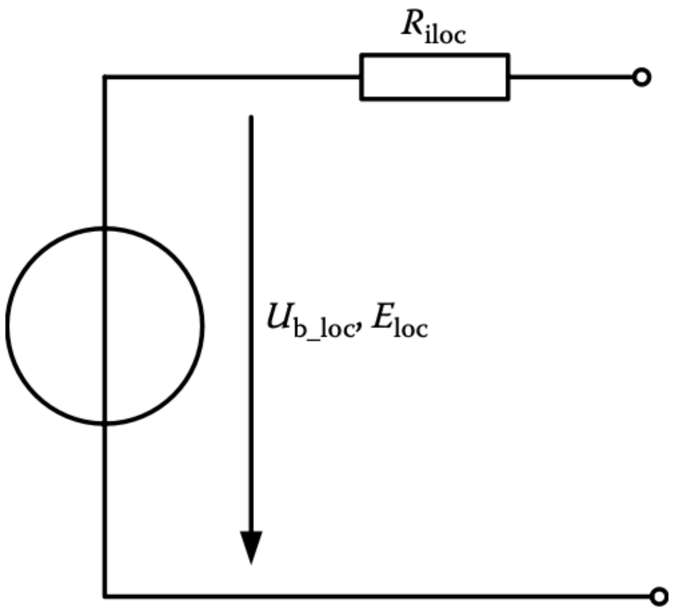
- ❖ The goal of this exercise is to establish the importance of the different losses, to show what components have the most influence on the efficiency, and to show how the losses depend on the charging speed.

Solution

Model of the local battery

The local battery can be modelled through the equivalent scheme of Figure. The battery no-load voltage is,

U_{b_loc} =135×3.7 V=499.

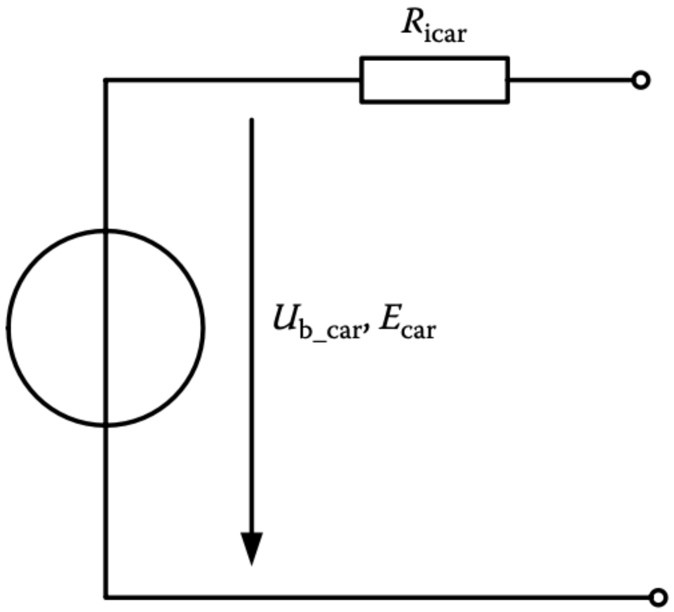


Simplified model of the local battery.

The internal resistance is,
R_{i_loc} =135×0.7 mw = 0.095 W
The battery energy capacity is
E_{loc}= 50 ah × 499.5 v = 24.975 kwh model of the car battery

Model of the car battery

The car battery can be modelled through the equivalent scheme of figure. The battery no-load voltage is,



Simplified model of the car battery.

PV Panels

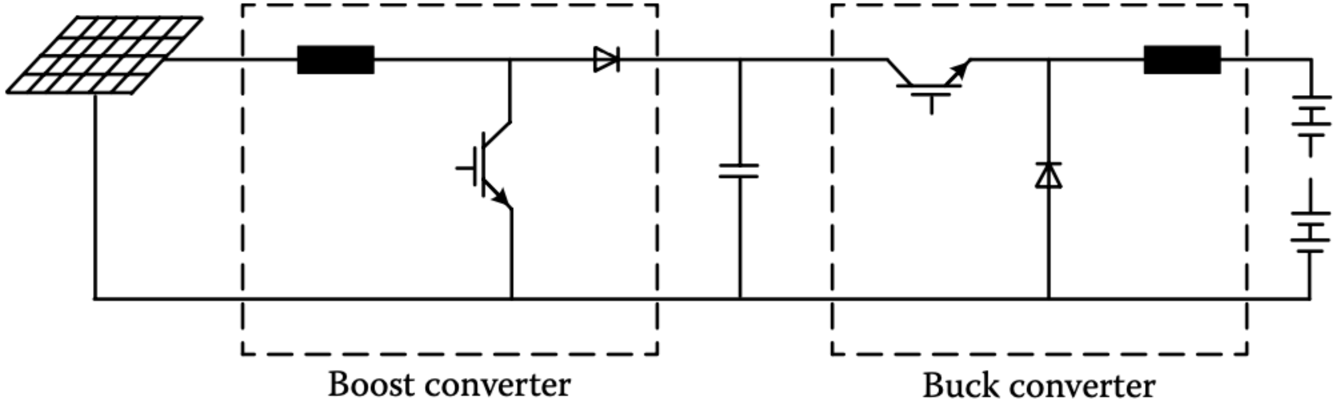


Fig5.4: Charging system of the local battery from PV panels.

The slow charge (7h) of 80% of the (local) battery capacity defines the charging power:

$$P_{80\%} = \frac{0.8 \times 24.975\ kWh}{7h} = 2.85\ kW$$

The solar (irradiance) power is consequently

$$\mathrm{P_{sol}} = \frac{\mathrm{P_{80\%}}}{\eta} = \frac{2.85\ \mathrm{kW}}{0.1} = 28.5\ \mathrm{kW}$$

For a simplified design of the PV generator, the supposition is made that the solar irradiance is of a constant average value of 800 W/m2 during 7 h. The PV panel surface becomes

$$\boldsymbol{S_{PV} = \frac{28.5kW}{800\,{}^{W}/_{m^2}} = 35.7m^2}$$

Charging in 7 h

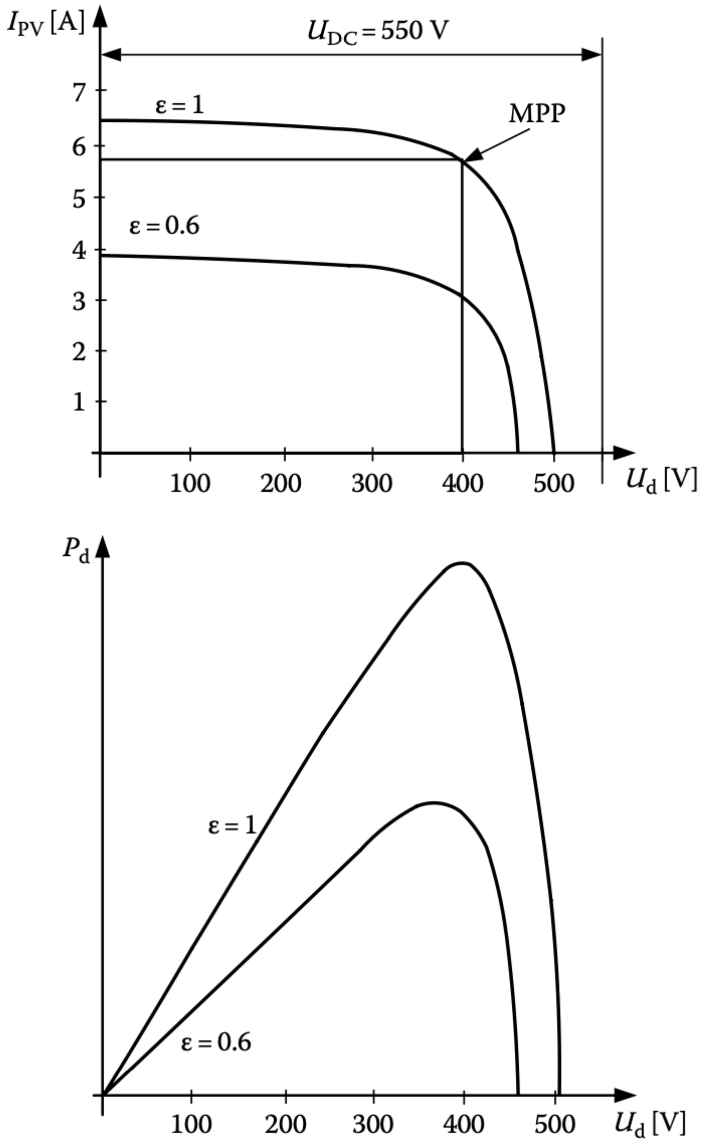
The charging current is calculated as (80% of battery capacity in 7 h):

$$\boldsymbol{I_{ch} = \frac{0.8 \times 50Ah}{7h} = 5.71A}$$

The power produced by the PV panels is transferred to the intermediate DC circuit with the help of the boost converter. This converter assumes the function of the adaptation of the voltage of the panels to a constant DC voltage. In addition, this converter allows the optimal operation of the PV panels at their point of maximum power (MPPT).

Characteristic Curve

- The characteristic curves of the PV panels are represented below. The voltage of the intermediate DC circuit is also represented (U_{DC} = 550 V). This value allows the boost converter to be operated with any value of the voltage of the PV panels. The represented MPP point corresponds to the maximum of power under a solar irradiance of ε = 1 and a temperature θ = 0°.
- From the intermediate circuit, the power is transferred to the local battery using the buck converter. This converter assumes the transfer of power under constant current control.
- The use of the cascade of a boost and of a buck converter implies a slightly reduced energy efficiency due to the double conversion. However, the main advantage is that the current at both the input and the output sides is non-discontinuous.

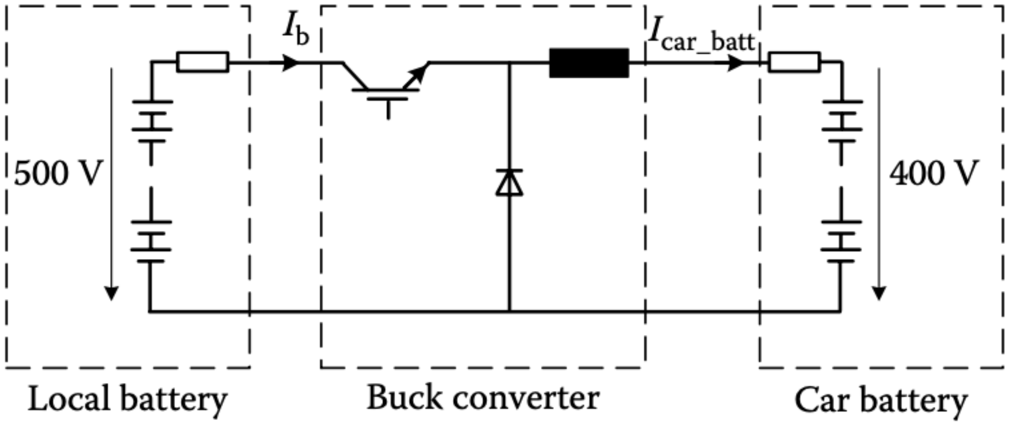


Characteristics of the PV panels.

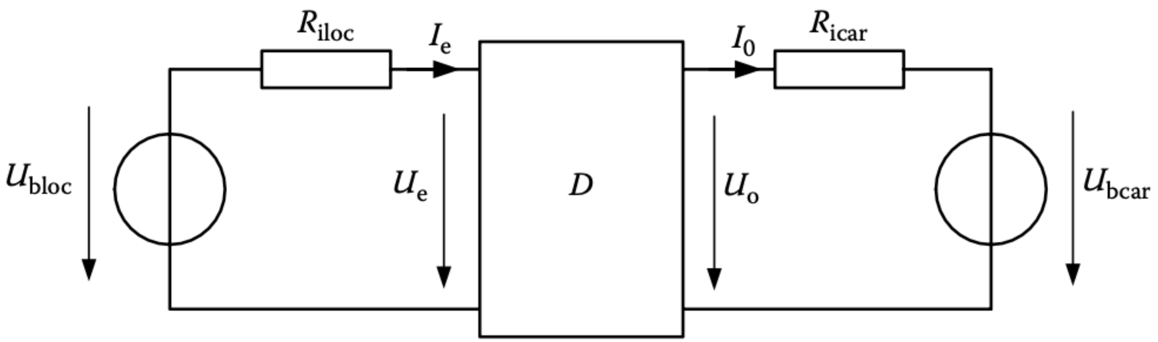
Fast charge from the buffer

To estimate the energy efficiency of the fast charge, the following elements are considered:

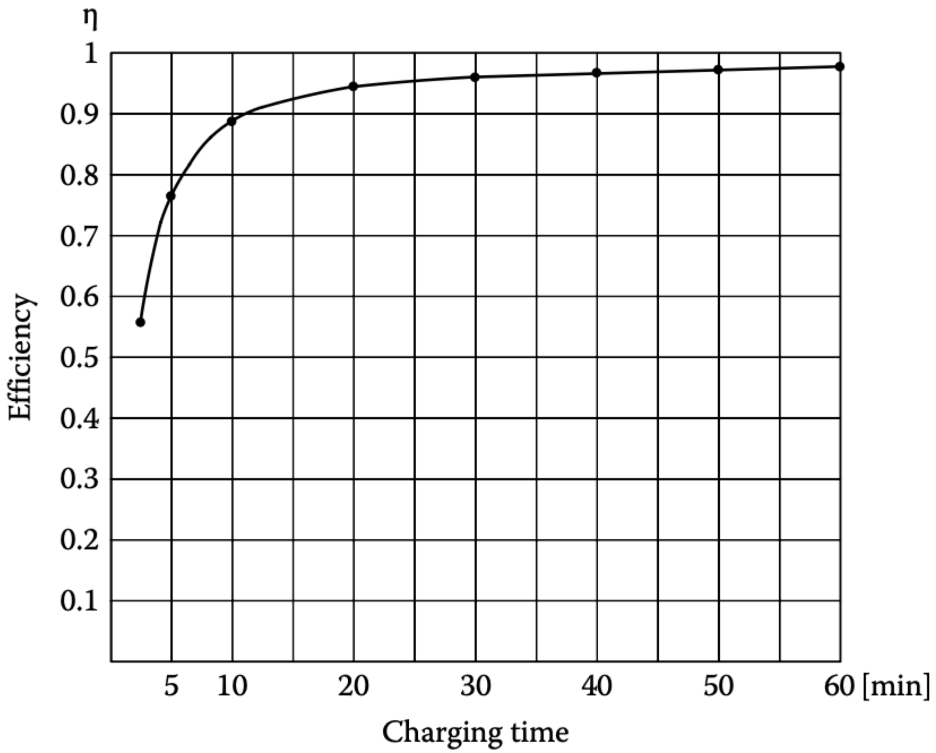
❖ Ohmic losses in the local battery.
❖ Ohmic losses in the car battery.
❖ Conduction losses in the power semiconductors.



Scheme for the fast charge from the buffer battery.



Equivalent scheme of the fast charge.



Efficiency as a function of the charging time.

Battery Energy Storage Capacity

- The energy storage capacity of a battery is given by the product of the battery's voltage and its capacity in ampere-hours (Ah):

$$E_{battery} = V \times Q$$

Where,

- $E_{battery}$ = Energy stored in the battery (in watt-hours, Wh)
- V = Nominal voltage of the battery (in volts, V)
- Q = Capacity of the battery (in ampere-hours, Ah):
- For example, a battery with a voltage of 400V and a capacity of 100Ah would have an energy storage capacity of,
- $E_{battery}$ =400V×100Ah=40,000Wh

State of Charge (SoC) Calculation

- The State of Charge (SoC) of a battery indicates the current charge level as a percentage of its total capacity:

$$SoC = \frac{Q_{remaining}}{Q_{total}} \times 100\%$$

Where,

- $Q_{remaining}$ = Remaining battery capacity (in Ah).
- Q_{total} = Total battery capacity (in Ah).
- For example, if the battery has 50Ah remaining out of a total of 100Ah,
- SoC=(50Ah of 100Ah)×100%=50%

Vehicle Range Estimation

- The estimated range of a BEV can be calculated using the energy consumption rate and the battery's energy capacity:

$$\text{Range}=\frac{E_{battery}}{C}$$

Where,

- Range = Estimated driving range (in kilometres or miles).
- $E_{battery}$ = Energy storage capacity of the battery (in kWh).
- C = Energy consumption rate (in kWh per km or mile).
- For example, if a BEVs has a 60 kWh battery and consumes 0.15 kWh per km,
- Range=60kWh0.15kWh/km=400km

Regenerative Braking Energy Recovery

❖ Regenerative braking allows the vehicle to recover some of the kinetic energy during deceleration. The energy recovered can be estimated by:

$$E_{regen} = \eta_{regen} \times \frac{1}{2} m v^2$$

Where,

•E_{regen} = Energy recovered during regenerative braking (in joules, J)

•η_{regen} = Efficiency of the regenerative braking system (typically between 50-70%)

•m = Mass of the vehicle (in kilograms, kg)

•v = Velocity of the vehicle before braking (in meters per second, m/s)

For example, if a 1500 kg vehicle travelling at 20 m/s (72 km/h) uses regenerative braking with 60% efficiency:

E_{regen} =0.6×(1/2)×1500kg× $(20m/s)^2$

Battery Discharge Rate

- The rate at which a battery discharges during operation can be described by:

$$I_{discharge} = \frac{P_{motor}}{V},$$

Where,

- $I_{discharge}$ = Discharge current (in amperes, A)
- P_{motor} = Power required by the electric motor (in watts, W)
- V = Voltage of the battery (in volts, V)
- If a motor requires 50 kW of power and the battery voltage is 400V,
- $I_{discharge} = \frac{50{,}000W}{400V} = 125A$

Numerical Problem

A certain electric vehicle (EV) is equipped with a 75 kWh lithium-ion battery pack. The vehicle has the following parameters:

Total Energy Capacity (E): 75 kWh

Current State of Charge (SoC): 60%

Average Power Consumption (P): 20 kWh/100 km

Regenerative Braking Efficiency (η_{rb}): 60%

Braking Energy Available for Recovery: 5 kWh

Distance Driven without Regenerative Braking (d): 50 km

Battery Discharge Rate (r): 10 kW (constant discharge during driving)

Numerical Problem

Questions

1: What is the available energy in the battery (in kWh) given the current State of Charge (SoC)?

2: Estimate how much further (in km) the vehicle can travel with the remaining energy in the battery. Assume no regenerative braking for this part.

3: How much energy is recovered during braking and how does it affect the total energy available?

4: How much further can the vehicle travel considering regenerative braking energy recovery?

5: If the vehicle is driving at a constant rate, how long (in hours) will it take for the battery to fully discharge?

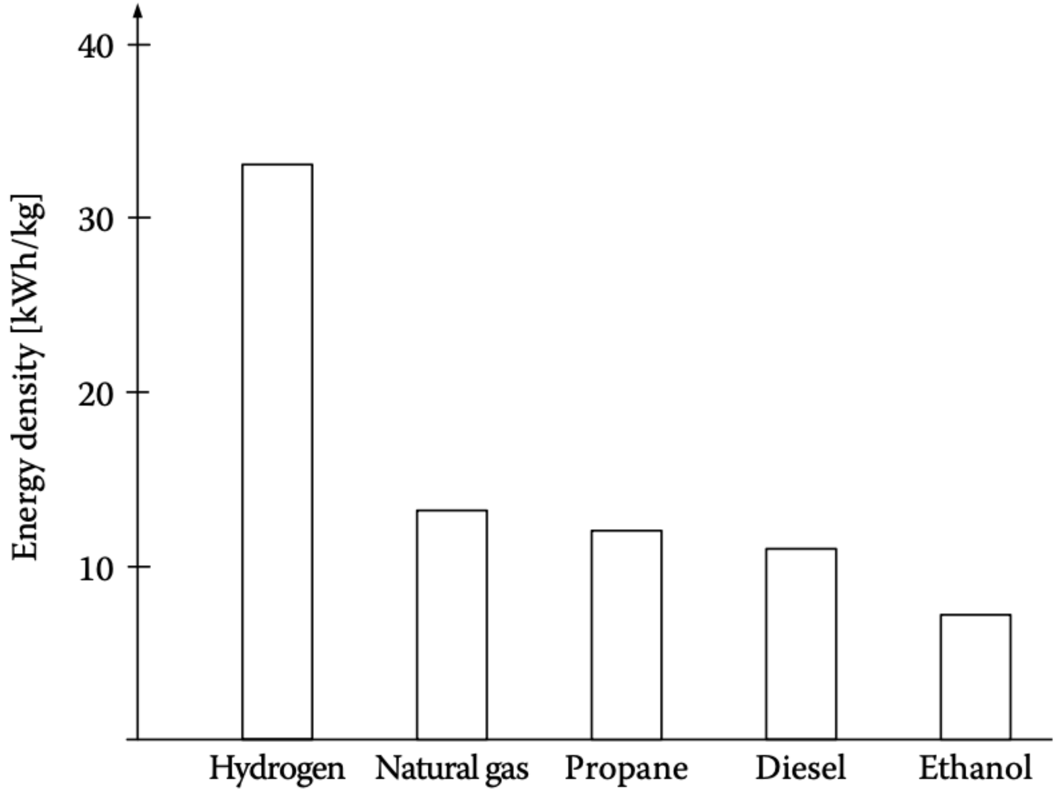
Fuel Cell based energy storage (Hydrogen)

- Hydrogen can be used for energy storage as an energy carrier due to its high energy density of 33 kWh/kg. This high value makes hydrogen a possible candidate for mid and long-term storage, as typically the so-called seasonal storage in the context of renewable energy sources.
- Compared to other fuels, hydrogen contains 3 times more energy than diesel fuel, and 2.5 times more than natural gas. Hydrogen can be produced from electricity using electrolyzers, and the reverse transformation from hydrogen to electricity can be carried out using a fuel cell.
- However, hydrogen is difficult to store, due to its very low weight density. At atmospheric pressure and ambient temperature, 1 kg of hydrogen needs a storage volume of 11 m3. As a consequence, hydrogen is usually compressed at a high-pressure level of between 350 and 700 bar. This high pressure addresses the question of the volume and weight needed for the reservoir, as well as the required energy for compression.

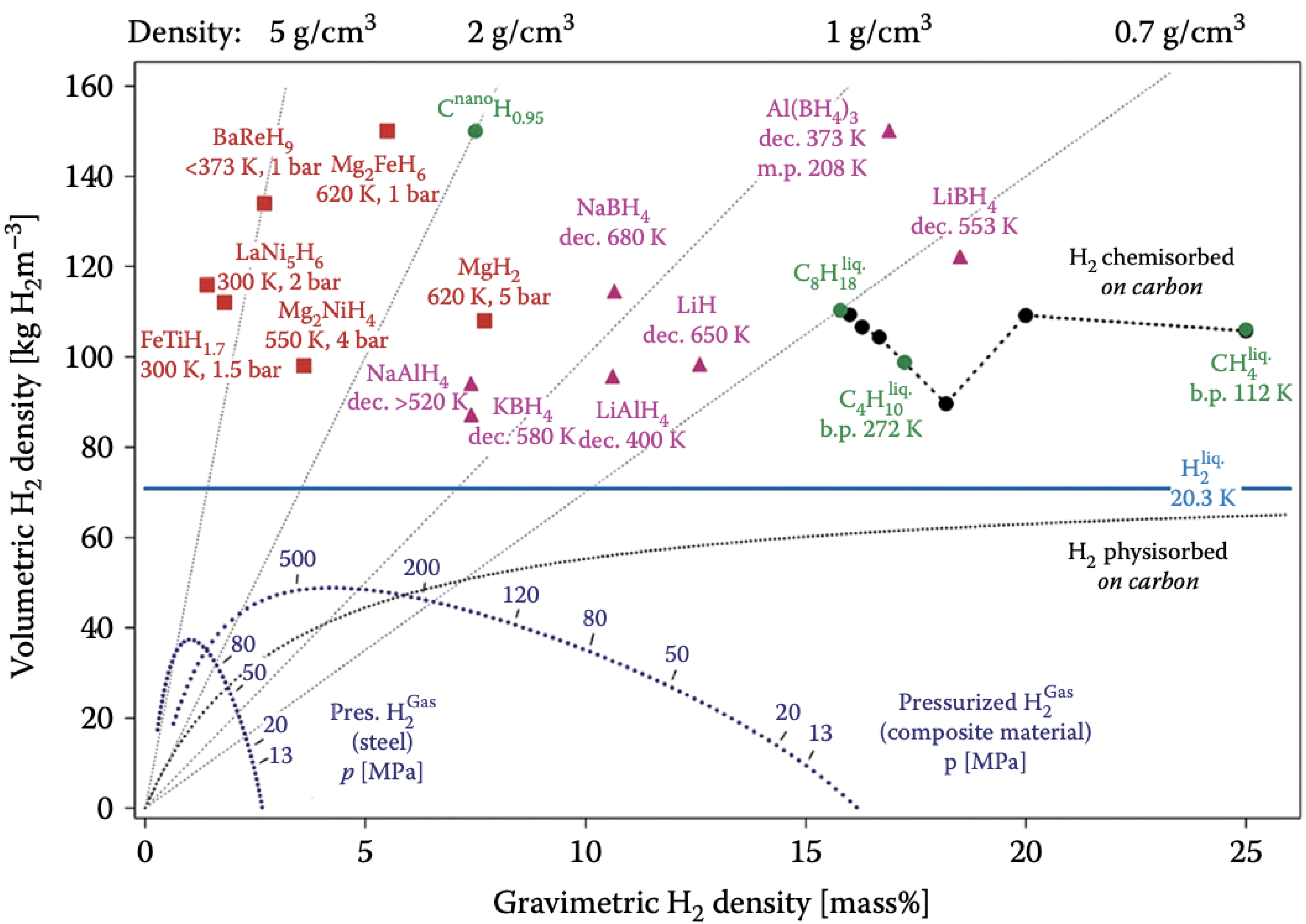
- ❖ The different energy densities of important energy vectors such as hydrogen, natural gas, propane, diesel fuel, and ethanol.
- ❖ Energy densities of different storage means have been presented, where typically a powerful Li-ion battery appears with “only” 0.15 kWh/kg.
- ❖ Hydrogen must be conditioned in order to express a valid energy density corresponding to a real application, in the sense that the storage volume can be reduced.

Three main techniques can be used for the volume reduction:

1. Storage of hydrogen as compressed gas (350–700 bar)
2. Storage of hydrogen in its liquid phase (−253°C)
3. Storage of hydrogen in a solid form



Energy densities.

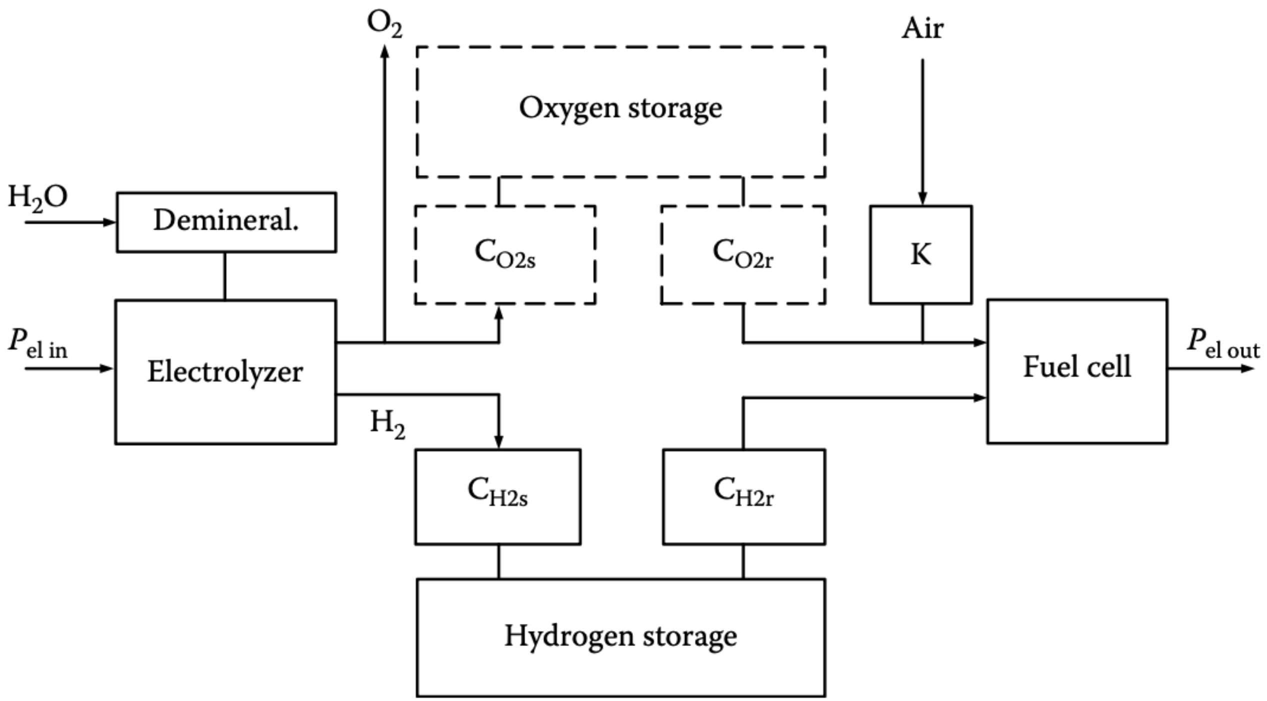


Volumetric and gravimetric hydrogen density of different selected hydrides. Mg_2FeH_6 shows the highest known volumetric hydrogen density of 150 kg/m3, which is more than double that of liquid hydrogen.

POWER-TO-POWER STORAGE SYSTEM (ESS-ELECTRICAL STORAGE SYSTEM) BASED ON HYDROGEN

- An electrical energy storage system (ESS) is defined as 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, is mentioned.
- An ESS or power-to-power storage system based on hydrogen can be carried out using a water electrolyzer and a fuel cell for the intermediate conversions. In addition to these intermediate conversions, hydrogen and oxygen conditioning systems are needed to elevate the volumetric energy density. Figure shows the elementary structure of an ESS based on hydrogen.
- The basic components of the system are the electrolyzer, the hydro- gen storage, and the fuel cell. Between the electrolyzer 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}).

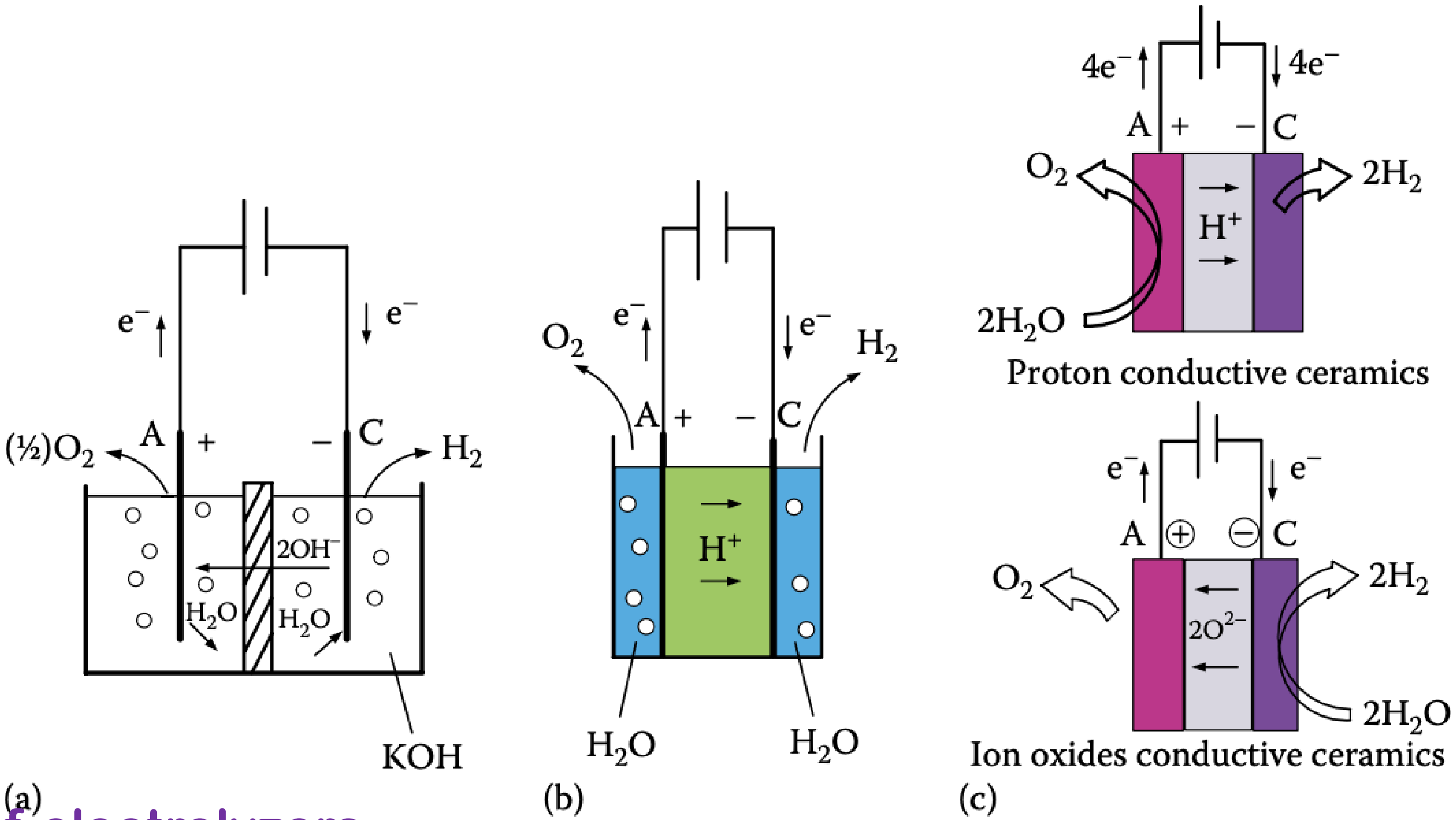
- For this purpose, an air compressor is represented (K). For the case of using stored oxygen, the conditioning blocks are represented (C_{O2s}, C_{O2r}).
- The conditioning devices for the storage process (C_{H2s}, C_{O2s}) are generally compressors or liquefiers, while the recovery conditioning devices (C_{H2s}, C_{O2s}) are simple relieve valves. In the case of solid storage of hydrogen in the form of metal hydrides, the conditioning processes are more complex.



Structure of a storage system based on hydrogen.

- An electrolyzer is a device for the chemical decomposition of water by the circulation of an electric current. It comprises two electrodes, the anode and the cathode, separated by an electrolyte. The electrodes are connected to a DC current source allowing the circulation of the current, and the electrolyte is the internal ionic conductive means.
- Three types of water electrolyzers have been developed or are under research. The most used system is the alkaline electrolyzer. Then there are solid polymer electrolyzers (SPE), where a proton exchange membrane is used as in a PEM fuel cell. Finally, a younger technique is based on the electrolysis of water vapour at high temperatures utilizing solid oxide electrolytes (SOEs).
- Figure illustrates the three electrolyzers according to the principles described in the next section.

Electrolysis of water



Three types of electrolyzers

(a) An alkalinelectrolysis,

(b) PEM electrolysis, and

(c) High-temperature steam electrolysis.

MATLAB Simulation

- Design, simulate, and optimize the performance of a hydrogen production system using a hydrogen electrolyzer model with functional details for component and balance-of-plant sizing.
- Develop and fine-tune an electrolyzer control system using a hydrogen electrolyzer model suitable for hardware-in-the-loop testing.
- Simulate hydrogen electrolyzer behaviors with different component specifications and under different operating conditions.

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CONVERSION FROM HYDROGEN TO ELECTRICITY

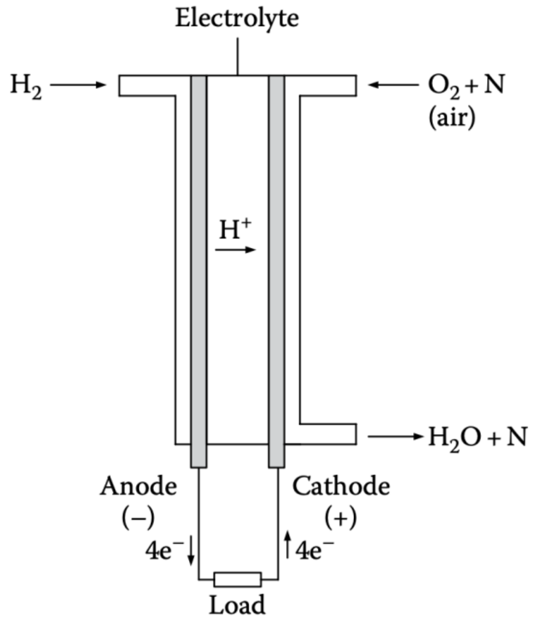
- In the structural diagram, the output stage of the system that converts the stored hydrogen into electric power is a fuel cell. A fuel cell allows the direct conversion of hydrogen into current, by chemical reaction between the hydrogen and oxygen. In conventional fuel cells, the oxidant is generally taken from the ambient air.
- The schematic diagram shows the main components: a classical PEM fuel cell with hydrogen and air supply. For such a fuel cell, the energetic balance must be evaluated in detail, considering the necessary power for the air compressor when it is operated at partial load. Load current proportional airflow can be a well-adapted control method.
- **Anode:**

$$H_2 \rightarrow 2H^+ + 2e^-$$

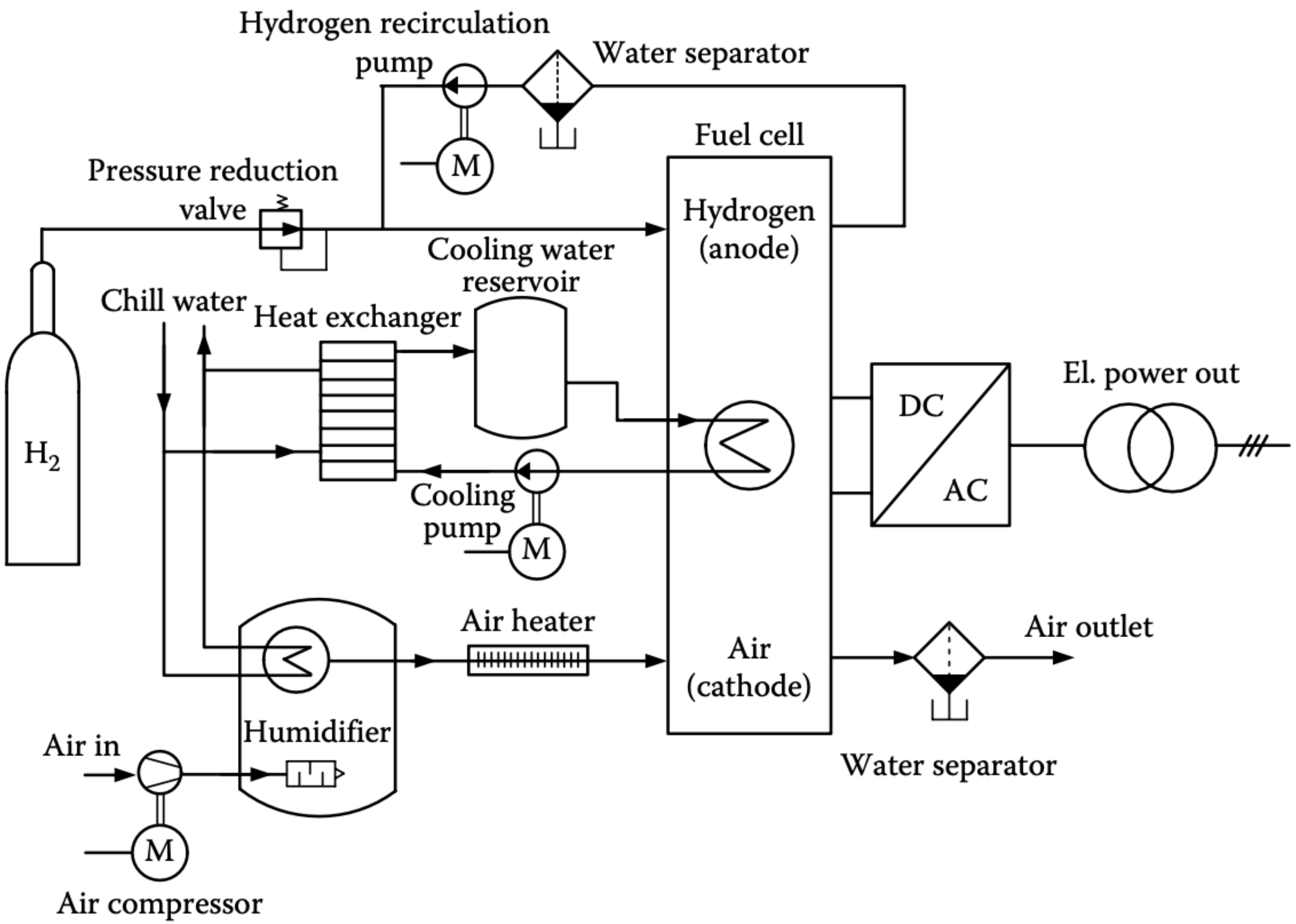
- **Cathode:**

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

❖ The energy efficiency of a hydrogen-based storage system can be calculated by the product of the partial efficiencies of the subcomponents. The first of these components is the electrolyzer, then the hydrogen and eventually the oxygen conditioning devices must be considered, and, finally, the back transformation from chemical to electric power in a fuel cell largely influences the global system efficiency.



Standard structure of a PEM fuel cell.



Fuel cell system. (Adapted from Grasser, F. and Rufer, A., PEMFC system efficiency optimization through model based control strategies, *IEEE VPC Vehicular Power and Propulsion Conference*, Windsor, England, September 6–8, 2006.)

Overall efficiency

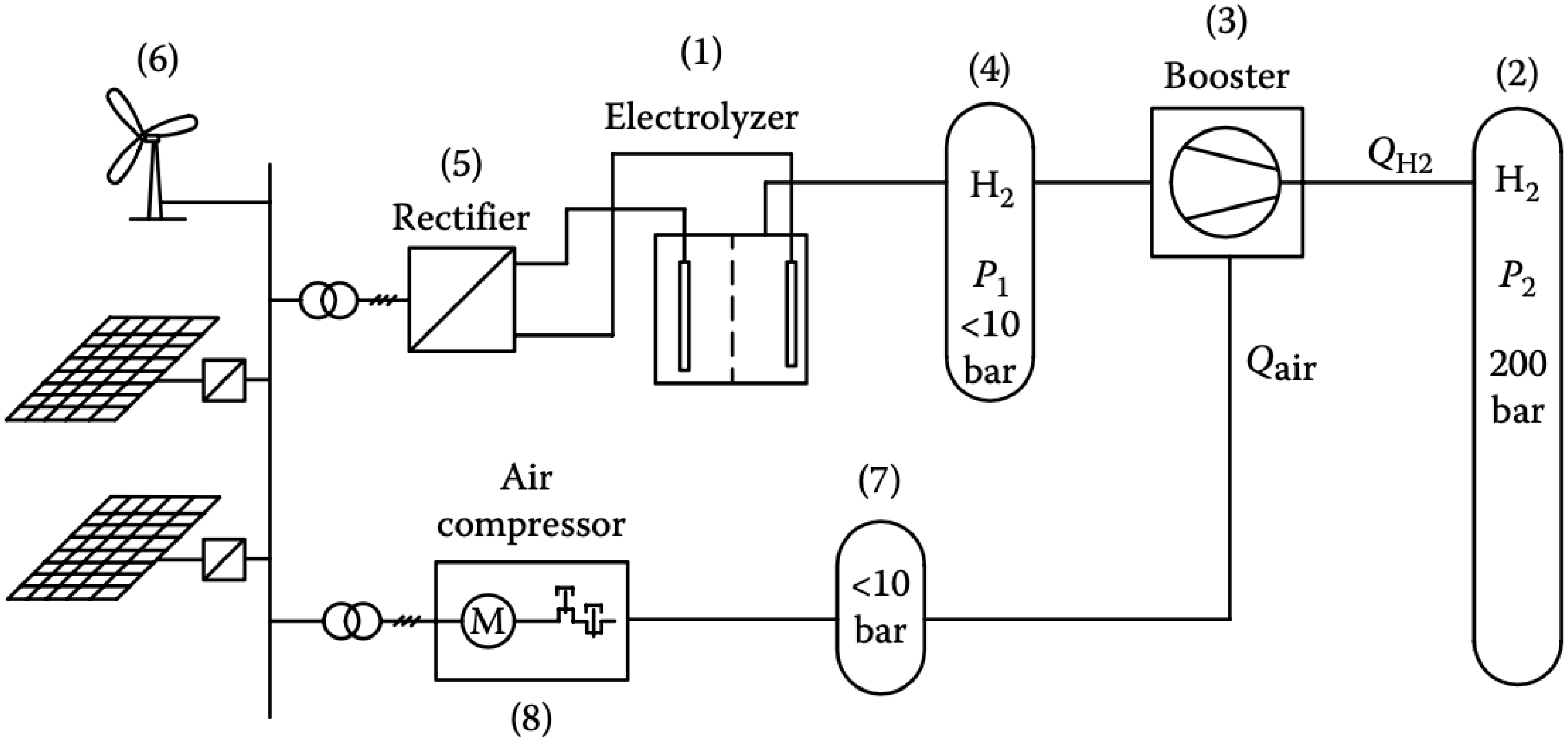
- The overall efficiency of the hydrogen storage defined as the ratio of the electrical output energy to the electrical input energy can be evaluated as,

$$\eta_{global} = \eta_{elys} \cdot \eta_{con} \cdot \eta_{fc}$$

- The use of electrolyzers directly producing hydrogen under pressure or high-temperature electrolyzers that can reuse the thermal dissipation of the fuel cell will lead to higher energy efficiency of 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 renewable energy resources.

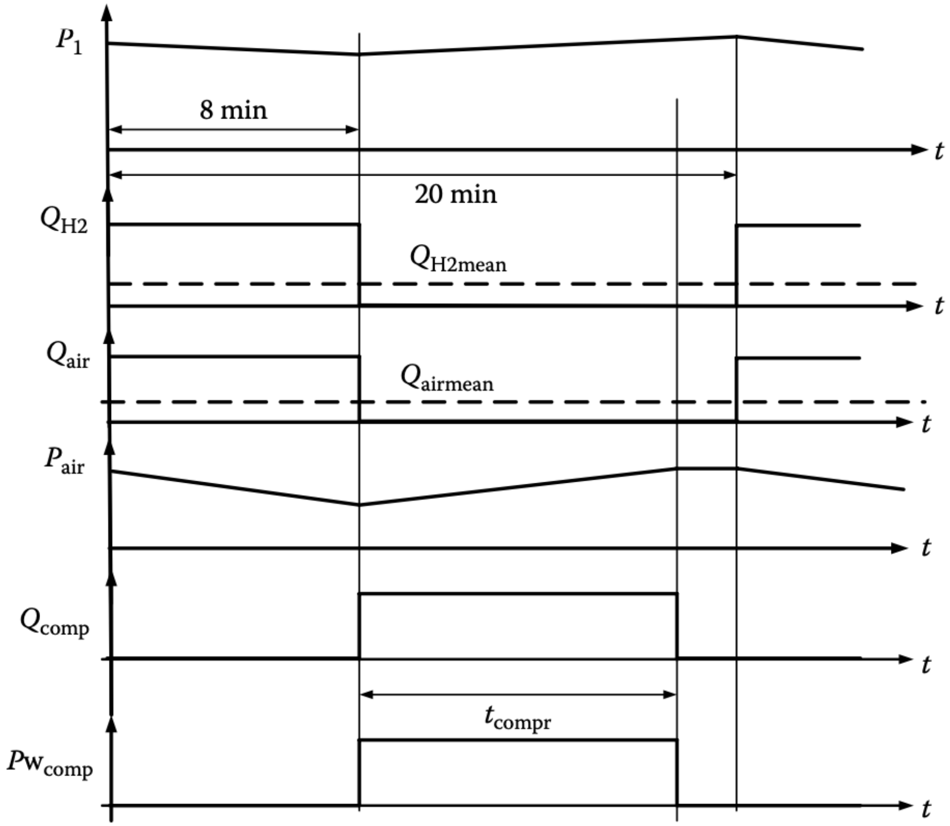
Conversion from electric power to hydrogen

- Larger amounts of energy can be stored chemically through conversion from electric power into pressurized hydrogen. An electrolyzer (1) is converting the electricity into hydrogen, which is stored in a final reservoir at a pressure of 200 bar (2). The filling of the final reservoir is achieved using a so-called booster station (3). This device is connected to an intermediate buffer-reservoir (4) fed directly from the electrolyzer.
- The electrolyzer is fed with electric current from a dedicated rectifier (5), itself connected to a local grid with renewable energy sources.
- The booster station comprises a reciprocating compressor, where the movement is produced with an air drive system. The air drive system is supplied by low-pressure air (industrial air) provided by an air compressor and reservoir ((8) and (7)). The goal of the exercise is to study such a system and to evaluate the energy efficiency of such a transformation.



Hydrogen storage for renewable energy sources based on electrolysis.

❖ The operation conditions are illustrated by the time diagram in Figure. The first line shows the variation of pressure in the intermediate hydrogen reservoir. The discharge is caused by the activation of the booster station during 8 min. This discharge is followed by a phase of depressurization of 12 min due to the operation of the electrolyzer. The total cycle time is 20 min.



Time schedule of the hydrogen compression system.

Thankyou