SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING
LRESE - Laboratory of Renewable Energy Sciences and Engineering

Renewable Energy: Exercise Energy Storage

In this exercise, you will learn about various energy storage solutions.

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1. Application of flywheels in cars: Two different applications of flywheels in cars are discussed here. In the first scenario, a flywheel is used as a replacement of a car's internal combustion engine (ICE). In the second scenario, a flywheel is considered as a supplementary energy storage which transforms kinetic energy into rotational energy during braking and supports the ICE during acceleration of the car.

   (a) How much kinetic energy is involved in the motion of a typical car (mass 1300 kg) at a speed of 80 km/h?

   (b) What amount of engine power is necessary to maintain this speed when only air resistance is considered? Assume drag coefficient of 0.31, front surface area of 2.2 m^2, and air density of 1.2 kg/m^3.

   (c) Consider the flywheel as replacement for the engine of such a car. How much energy would have to be stored in such a flywheel engine if the driving range were 120 km and achieved by driving at a constant speed of 80 km/h. Assume a drivetrain efficiency of the car of 70 %.

   (d) Of what size and weight would such a flywheel engine be? How fast would it rotate? Dimension an engine that consists of two identical counter rotating flywheels made of carbon-fiber-reinforced plastic. Assume the ultimate strength of the material to be 2000 N/mm^2 and its density to be 1500 kg/m^3. The shape factor of the flywheel is 0.606. Due to size limitation of the car, there is only space for wheels of a maximum radius of 70 cm and therefore R is set to 70 cm.

   (e) In towns, traffic often doesn't move smoothly with constant speed. Due to narrow streets, heavy traffic and traffic light, cars continuously accelerate and brake. During breaking kinetic energy is normally transformed to heat. With a small pair of flywheels, this energy could be stored and reused to accelerate the car. Dimension a flywheel that would support a conventional engine during acceleration (up to 120 km/h). There is less space for a supplementary device. As a consequence, the radius of the flywheels R is set to 30 cm. Determine the size, weight and rotational speed of the flywheels.

2. Compressed air storage: If compression and expansion of air were isothermal and fully reversible, the efficiency of compressed air storage would only be limited by the efficiencies of the pump and generator. But when air is expanded in a short time, the air doesn't exchange much heat with its surrounding and its temperature drops. With an adiabatic expansion, followed by an isobaric one, less energy is transformed to work than with an isothermal process.

(a) Assume the air compression to be isothermal and the expansion to be adabatic. Draw the pV-diagram which shows this compression-expansion cycle.

(b) Calculate the amount of exergy which is lost due to the fact that the air expansion is adiabatic instead of isothermal. Assume gas tank pressure of 300 bar, and c_p/c_v=1.4)

(c) Would it be convenient to replace tank and engine of a car with a compressed air tank (pressure 300 bar) and a corresponding engine? How large has this tank to be, if a driving range of 120 km (at a constant speed of 80 km/h) is desired? Assume adiabatic expansion and neglect losses in the engine. For simplicity, you may also assume that the car maintains at 80 km/h already and it accounts for the energy loss to overcome air drag only. Take the car data from problem 1.

3. Pumped water storage

   (a) Assume a dam with a higher reservoir located at 1800 m over sea and its lower reservoir at 800 m. How much water has to be pumped from the lower reservoir to the higher one to store the yearly production of a 100 MW_p photovoltaic plant? Assume the average power of the plant to be 15% of the peak power. The pump efficiency is assumed to be 85%.

   (b) How much water would it be for a 100 MW_{av} PV plant?

4. Battery: Consider a lead-acid battery with the standard overall reaction:
   $Pb + PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O$

   (a) Write down the half-cell reactions at the anode and cathode during discharging the battery

   (b) Calcualte the reversible cell potential at standard condition. Assume ΔG^0 = -395 kJ/mol. How many of this single units do you have to connect in series if a battery block with 24 V is needed?

   (c) How many hours will it take to recharge the battery at a current of 1.5 A when 11.6 g of Pb is converted to $PbSO_4$?

   (d) Calculate the mass specific charge density and the mass specific energy density of the electrode material when charged.

   (e) Now consider a common Li-ion battery, the Li-CoO_2 cell: $LiC_6 + CoO_2 \longleftrightarrow 6C + LiCoO_2$
   a. Calculate its reversible cell potential at standard condition. Assume ΔG^0 = -405 kJ/mol
   b. Compare the mass specific charge density and mass specific energy density to the values of the lead-acid battery
   c. What are the two main reasons for this difference?