Hydrogen has the potential to become a clean energy carrier when produced via electrolysis (green hydrogen). However, hydrogen storing is challenging due to the extremely low density. At room temperature and standard pressure, 1 kg of hydrogen gas occupies 12 m^3. Therefore, H_2 must be compressed to make it practical for transport, fueling stations, and industrial use.

In this exercise we will study the compression cost of hydrogen and compare different techniques for hydrogen storage to see how this cost can be reduced.

Part 1

In a single-stage compressor, two different methods can be used: adiabatic and isothermal compression.

In the isothermal compression, heat is removed to keep the temperature constant, hence, the compression work required is reduced. While in the adiabatic compression, no heat is removed, hence, the temperature increases, which requires more compression work. Isothermal compression is a slow process and is used for energy storage, while adiabatic compression is a fast process and is used in internal combustion engines as well as air conditioning and refrigeration.

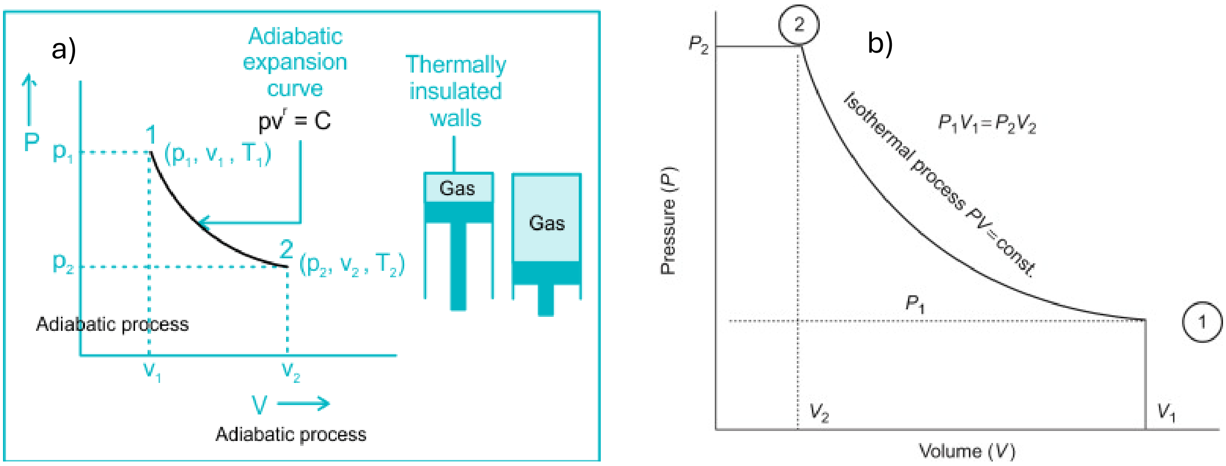


Figure 1: a) Adiabatic compression process b) Isothermal compression process

Knowing that the total work done *on* the gas is the integral of the pressure-volume work from V_1 to V_2 given as:

$$W = -\int_{V_1}^{V_2} P\, dV$$

a) Using the ideal gas law, derive the adiabatic and isothermal compression work formula as a function of P_1, P_2, C_p, T, γ and η_c, where P_1 and P_2 are the initial and final pressures respectively, C_p the compressed gas specific heat, T the temperature, γ the specific heat ratio and η_c the compressor mechanical efficiency.

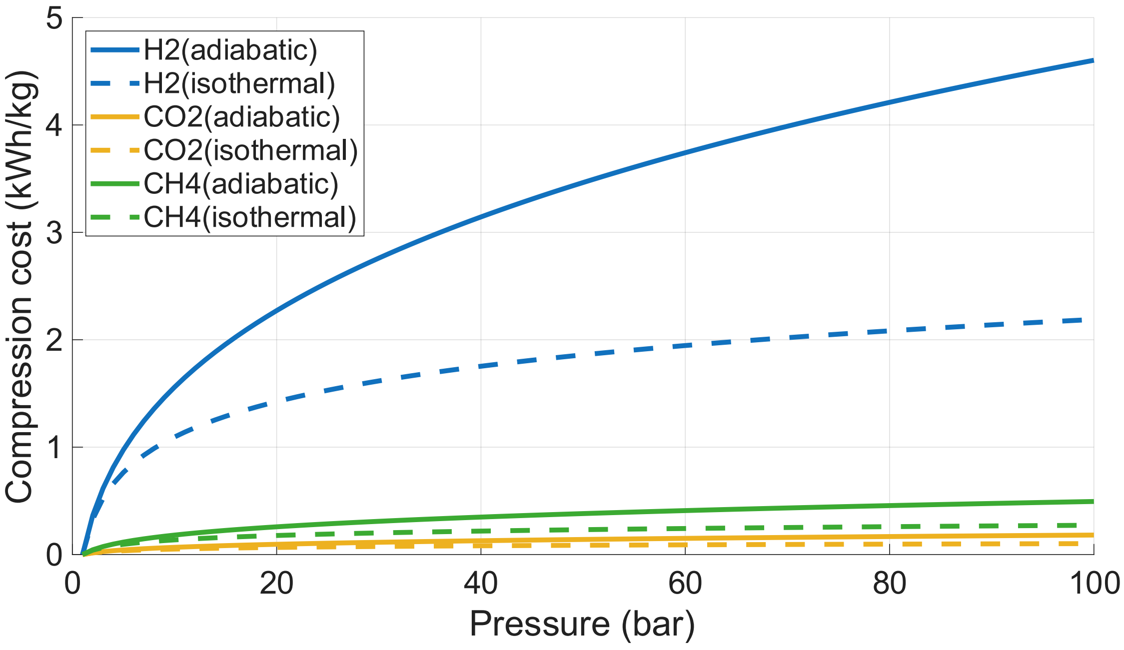
b) Using the derived formulas, plot the adiabatic and isothermal compression cost curve as a function of pressure for H_2, CH_4, and CO_2, when compressed from 1 bar up to 100 bar. Assume 70% mechanical efficiency.

c) What observations can you make from the plots?

$$H_2: \begin{cases} c_{p,H2} = 14'304\ [\frac{J}{kg \cdot K}] \\ \gamma_{H_2} = 1.41 \end{cases}$$

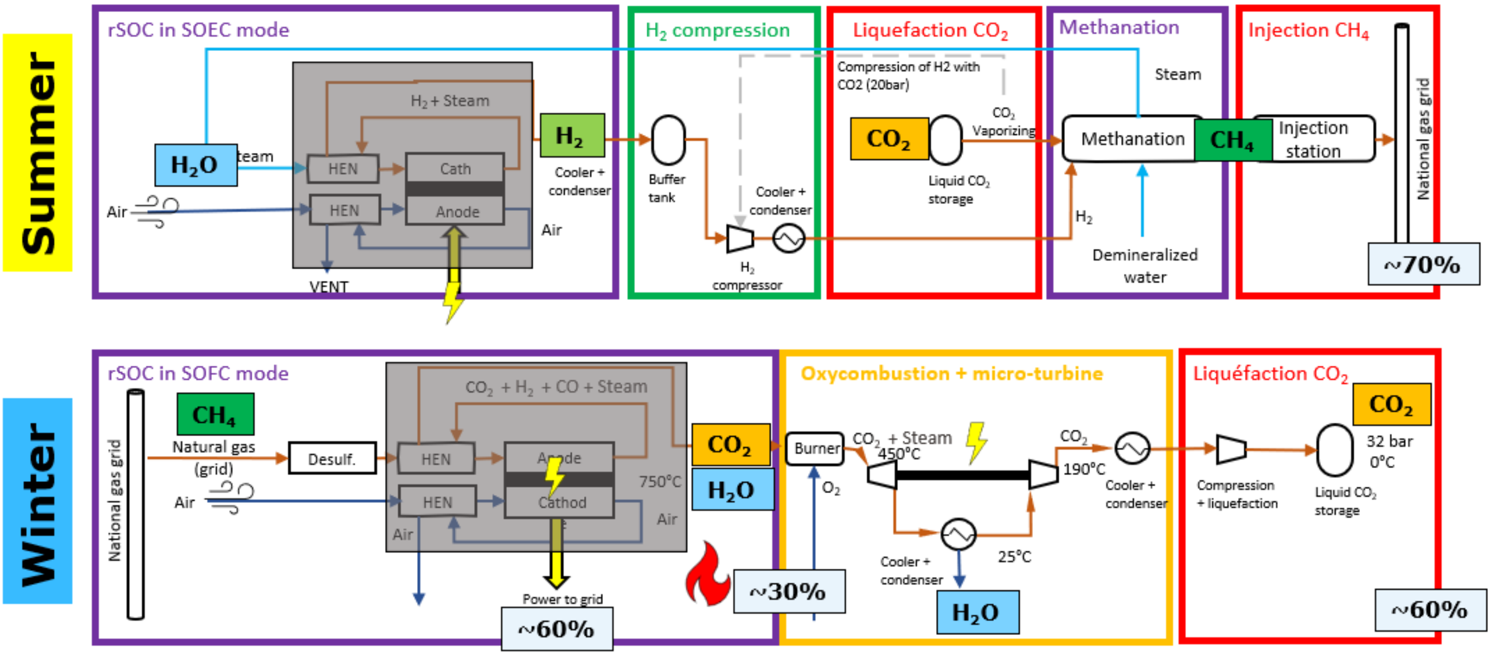
$$CH_4: \begin{cases} c_{p,H2} = 2'191\ [\frac{J}{kg \cdot K}] \\ \gamma_{H_2} = 1.31 \end{cases}$$

$$CO_2: \begin{cases} c_{p,H2} = 839\ [\frac{J}{kg \cdot K}] \\ \gamma_{H_2} = 1.30 \end{cases}$$

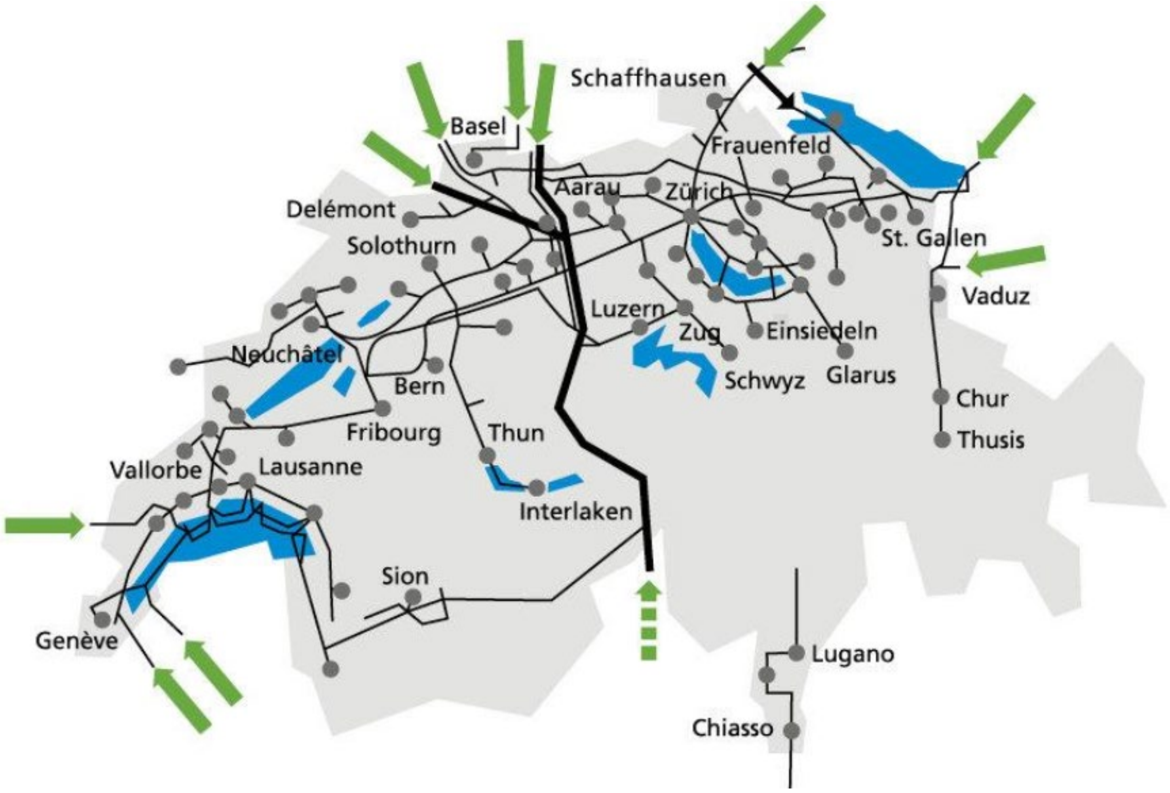


Part 2

Consider a reversible solid oxide cell (rSOC) used for seasonal storage. During summer, as shown in the figure below, the rSOC is used as electrolyzer (SOEC) to produce H2 from steam that is compressed and transferred into a methanator to produce methane by combining H2 and CO2. The pressurized methane is then sent into the national gas grid. In winter the rSOC is used in fuel cell mode (SOFC) to produce electricity from the stored CH4. A micro gas turbine is coupled to the anode exhaust gas of the SOFC to produce even more electricity. The product, pure CO2, is easily stored by a simple compression process. The CO2 is stored to be used for the methanation process during summer.



The solution of methane injection in a gas grid could be relatively easily implemented in countries where a national gas grid is well implemented such as Switzerland (figure below). It is not possible to transport hydrogen through the pipelines for the moment. The main gas grid is pressurized at 70 bar and made for methane. For industrial and local distribution, the pressure is lowered to 5 bar and for households the pressure is further lowered to a few mbar.



In winter, the SOFC is fueled with 0.96 kg/h of methane at atmospheric pressure, the electric output is 8.5 kW. The exhaust gases (remains of H2 and CO) are burned in a catalytic burner with pure O2 so that the combustion products are CO2 and H2O. The heated gases are then expanded into the micro gas turbine which produces an electrical output of 0.7 kW. To account for the pumps, blowers, and losses, 0.5 kW is removed from this production. At the turbine outlet, pure CO2 is compressed from atmospheric pressure to 35 bar and 0°C for storage as a liquid.

In summer, the fuel cell works in electrolyzer mode at 24 kW. The production is 0.7 kg/h of hydrogen. This hydrogen is compressed from 1 bar to 30 bar to enter the methanation part. The hydrogen is then combined with CO2 to produce CH4 and steam. The methanation process produces two flows, one of steam that is fueling the electrolyzer and the other flow is methane at 20 bar. The gas grid is set at 5 bar which means the expansion work from 30 to 5 bar could be recovered.

In case the methanation step is not included in the system, the produced hydrogen must be stored at a pressure of around 100 bar. To occupy less space, the pressure could be increased but at an important compression cost increase (specific volume of hydrogen = 11.12 m3/kg compared to methane at 1.39 m3/kg).

For the compression of CO_2, we take reference from the values of Atlas Copco and the CO_2 booster *CO2 2-195 – 50* that compresses CO_2 from 1 to 20 bar. The power consumption is found to be 0.173 kWh/kg.

a) Compare this value with the adiabatic and isothermal compressions. What can you comment?

b) Using the value of the *CO2 2-195 – 50* booster, calculate the compression power required to compress a mass flow CO_2 = 2.86 kg/h from 1 to 35 bar.

c) Find the system electric efficiency by performing the winter system energy balance assuming a mass flow of CO_2 = 2.86 kg/h and a low heating value of 50 MJ/kg for the methane.

During summer, we need to compress the produced H_2 from 1 to 20 bar. The multi-stage (5 stage) ionic compressor IC 50/30-S from Linde compresses hydrogen from 6 to 500 bar with a power consumption of 2.8 kWh/kg.

d) Compare this value with the adiabatic and isothermal compressions. What can you comment?

Henceforth, we will assume the ratio between the manufacturers value and the adiabatic/isothermal compression to be constant.

$$xW_{(comp,adiab)} + (1-x)W_{(comp,isot)} = W_{manufacturer} = constant \left[\frac{kWh}{kg}\right]$$

e) Using a mass flow of 0.7 kg/h, calculate the compression power for H_2 from 1 to 20 bar using the adiabatic and isothermal equations.

f) As the CO_2 is expanded from 35 bar to 20 bar and the produced methane is expanded from 20 to 5 bar, calculate the possible recovery power from these streams that could be used to partially compress the hydrogen.

g) Perform the summer system energy balance with a mass flow of CH_4 = 1.3 kg/h

h) Find the total round-trip efficiency

i) In the case without the methanation part, hydrogen must be compressed to 100 bar. Calculate the new required compression power for hydrogen and comment.