Exercise 1) A hydrogen-powered aircraft is an airplane that uses hydrogen fuel as a power source. Hydrogen can be either burned in a jet engine or another kind of internal combustion engine, or can be used to power a proton exchange membrane fuel cell to generate electricity to power a propeller.

1.1) Assuming that a Boeing 747 uses approximately 1 gallon of fuel (about 4 liters) every second. How much fuel is needed for a 10-hour flight?

= 3600s/h $\times$ 10 h $\times$ 1 gallon/s=36000 gallons = 150,000 liters

1.2) The official Boeing's website also has mentioned that Boeing's 747 uses 12 liters per kilometers. What would be the distance during the 10-hour flight?

= 150000 liters $\times$ 1/12 (kilometers/liters) = 12,500 kilometers.

1.3) With the declared price of ($3.04) in March 2022 for the jet-fuel per gallon. What would be the cost of the fuel for this flight?

=36000gallons $\times$ 3.04$/gallons= 109.440 $.

1.4) Considering the energy density of 35 MJ/L for the jet-fuel, what would be the produced energy during this flight?

= 35MJ/L $\times$ 150000 liters = 5,250 GJ

1.5) With the specific energy of (8.5 MJ/L) for Hydrogen fuels. What would be the needed space for hydrogen to produce the same amount of energy as the jet-fuel?

= 5250000 $\times$ 1/8.5 = 617,647 Liters = 154,411 gallons

1.6) Comparing the required space for the Kerosene based jet- fuel and the hydrogen fuel, how many more liters of fuel is needed for hydrogen-based airplanes?

= 617,647 – 150000 = 467,647 liters

1.7) With the specific energy of 43 MJ/kg for jet fuel, what would be the respective weight of the fuel for the kerosene-based airplanes?

= 5250000 $\times$ 1/43 = 122,093 kg

1.8) With the specific energy of 120 MJ/kg for hydrogen, what would be the respective weight of the fuel for the hydrogen-based airplanes?

= 5250000 $\times$ 1/120 = 43,750 kg

1.9) It is considered that Boeing 747 can carry as many as 568 people with the average weight of 80kg. How many passengers can fly if the fuel is hydrogen?

= (122,093-43,750)/80 +568= 1547 passengers

1.10) With the price of 16.51 $/kg for the hydrogen, how much this travel will cost to provide the hydrogen as the fuel?

= 16.51 $\times$ 43,750 = 722,313 $, approximately 7 times higher than kerosene based jet fuel.

1.11) The cheapest available engine for the Boeing 747 is the Pratt & Whitney JT9D turbofan, that four of them are needed for this type of plane. The four engines will approximately weights 16000 kg, costs $44 million, produce 44 MW, and need around 85 m^3, with 5000 hours lifetime. Also, the FCgen®-HPS model of Ballard PEM fuel cell, which has 484mm length, 555mm width, 195 mm height, and 60 kg weight. This type of fuel cell has the maximum power of 140 kW and it may cost around $55/kW. How many fuel cell stacks are needed to provide the needed power for the 10 hours flight of Boeing 747?

= 44000 / 140 = 314 FCgen®-HPS stacks

1.12) What would be the required weight of the fuel cell system to provide the mentioned power?

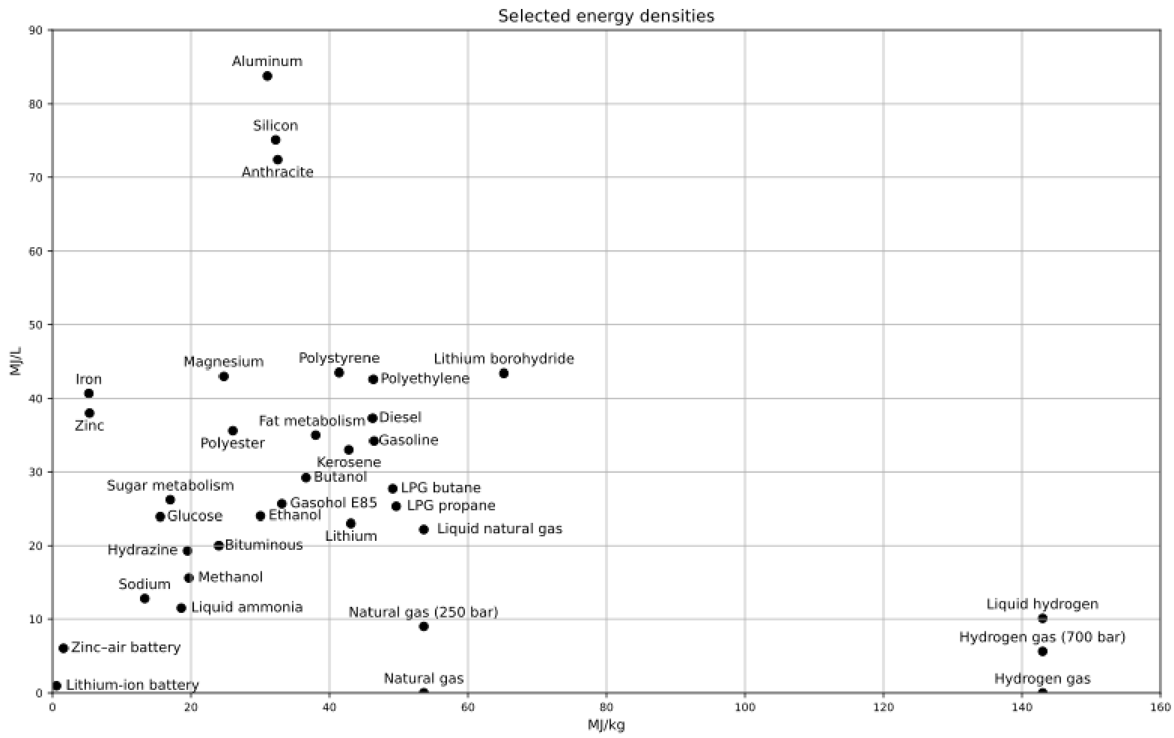
= 60 × 314= 18,857 kg

1.13) What would be the required space for the fuel cell system to provide the mentioned power?

= 0.484×0.555×0.195×314 = 16.447 m^3

1.14) What would be the cost of the fuel cell system?

= 55 × 44000 = $2420000 = % 2.42 million



Exercise 2) Packaging, transportation, storage, and transfer are the necessary steps to commercialize any products even for hydrogen and methane, which they have to be packaged by compression or liquefaction, and to be transported by vehicles or pipelines. Energy is needed to compress the gases. The compression work depends on the thermodynamic compression process. The ideal isothermal compression cannot be realized. The adiabatic compression equation is as follows:

$$W_{com} = \left(\frac{\gamma}{\gamma - 1}\right) P_0 V_0 \left(\left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{1}$$

where, W_{com} (J/kg) is the specific compression work, P_0 (Pa) is the initial pressure, P_1 (Pa) is the final pressure, V_0 (m^3/kg) is the initial specific volume, and γ is the ratio of specific heats, adiabatic coefficient. Eq. (1) is more closely describing the thermodynamic process for ideal gases. The compression work depends on the nature of the gas.

Table 1 The properties of Helium, hydrogen, and Methane.

	γ	V_0 (m^3/kg)
Hydrogen	1.41	11.11
Helium	1.66	5.56
Methane	1.31	1.39

2.1) Using the Eq. (1) and Table 1, what is the adiabatic compression energy of methane at 200, 400, 600, 800, and 1000 bars? (assume the initial pressure of 100 bar)

200bar: $W_{com}^{200bar} = \left(\frac{1.31}{1.31-1}\right) 10^7 \times 1.39 \left(\left(\frac{200}{100}\right)^{\frac{1.31-1}{1.31}} - 1\right) = 4220 \times 13900 \times 0.178 = 10\ MJ/kg$

400bar: $W_{com}^{200bar} = \left(\frac{1.31}{1.31-1}\right) 10^7 \times 1.39 \left(\left(\frac{400}{100}\right)^{\frac{1.31-1}{1.31}} - 1\right) = 4220 \times 13900 \times 0.389 = 22\ MJ/kg$

600bar: $W_{com}^{200bar} = \left(\frac{1.31}{1.31-1}\right) 10^7 \times 1.39 \left(\left(\frac{600}{100}\right)^{\frac{1.31-1}{1.31}} - 1\right) = 4220 \times 13900 \times 0.529 = 31\ MJ/kg$

800bar: $W_{com}^{200bar} = \left(\frac{1.31}{1.31-1}\right) 10^7 \times 1.39 \left(\left(\frac{800}{100}\right)^{\frac{1.31-1}{1.31}} - 1\right) = 4220 \times 13900 \times 0.637 = 37\ MJ/kg$

1000bar: $W_{com}^{200bar} = \left(\frac{1.31}{1.31-1}\right) 10^7 \times 1.39 \left(\left(\frac{1000}{100}\right)^{\frac{1.31-1}{1.31}} - 1\right) = 4220 \times 13900 \times 0.726 = 42\ MJ/kg$

2.2) Using the Eq. (1) and Table 1, what is the adiabatic compression energy of hydrogen at 200, 400, 600, 800, and 1000 bars? (assume the initial pressure of 100 bar)

200bar: $W_{com}^{200bar} = \left(\frac{1.41}{1.41-1}\right) 10^7 \times 11.11 \left(\left(\frac{200}{100}\right)^{\frac{1.41-1}{1.41}} - 1\right) = 382184000 \times 0.223 = 85\ MJ/kg$

400bar: $W_{com}^{200bar} = \left(\frac{1.41}{1.41-1}\right) 10^7 \times 11.11 \left(\left(\frac{400}{100}\right)^{\frac{1.41-1}{1.41}} - 1\right) = 382184000 \times 0.495 = 189\ MJ/kg$

600bar: $W_{com}^{200bar} = \left(\frac{1.41}{1.41-1}\right) 10^7 \times 11.11 \left(\left(\frac{600}{100}\right)^{\frac{1.41-1}{1.41}} - 1\right) = 382184000 \times 0.681 = 260\ MJ/kg$

800bar: $W_{com}^{200bar} = \left(\frac{1.41}{1.41-1}\right) 10^7 \times 11.11 \left(\left(\frac{800}{100}\right)^{\frac{1.41-1}{1.41}} - 1\right) = 382184000 \times 0.827 = 316\ MJ/kg$

1000bar: $W_{com}^{200bar} = \left(\frac{1.41}{1.41-1}\right) 10^7 \times 11.11 \left(\left(\frac{1000}{100}\right)^{\frac{1.41-1}{1.41}} - 1\right) = 382184000 \times 0.95 = 363\ MJ/kg$

Isothermal compression follows a simpler equation as follows:

$$W_{com} = P_0 V_0 \ln\left(\frac{P_1}{P_0}\right) \tag{2}$$

2.3) Using Eq. (2) and table 1, what is the isothermal compression energy of methane at 200, 400, 600, 800, and 1000 bar? (assume the initial pressure of 100 bar)

200bar: $W_{com}^{200bar} = 10^7 \times 1.39 \times \ln(2) = 9.6\ MJ/kg$

400bar: $W_{com}^{200bar} = 10^7 \times 1.39 \times \ln(4) = 19.3\ MJ/kg$

600bar: $W_{com}^{200bar} = 10^7 \times 1.39 \times \ln(6) = 24.9\ MJ/kg$

800bar: $W_{com}^{200bar} = 10^7 \times 1.39 \times \ln(8) = 28.9\ MJ/kg$

1000bar: $W_{com}^{200bar} = 10^7 \times 1.39 \times \ln(10) = 3.2\ MJ/kg$

2.4) Using Eq. (2) and table 1, what is the isothermal compression energy of hydrogen at 200, 400, 600, 800, and 1000 bar? (assume the initial pressure of 100 bar)

200bar: $W_{com}^{200bar} = 10^7 \times 11.11 \times \ln(2) = 77\ MJ/kg$

400bar: $W_{com}^{200bar} = 10^7 \times 11.11 \times \ln(4) = 154\ MJ/kg$

600bar: $W_{com}^{200bar} = 10^7 \times 11.11 \times \ln(6) = 199\ MJ/kg$

800bar: $W_{com}^{200bar} = 10^7 \times 11.11 \times \ln(8) = 231\ MJ/kg$

1000bar: $W_{com}^{200bar} = 10^7 \times 11.11 \times \ln(10) = 256\ MJ/kg$