2. This question is about making ammonia

The Haber process is used to make ammonia, the main use of which is in fertilisers that are often sprayed on crops. Around 1% of the entire global energy supply is used in the Haber process and so research groups are looking to find more sustainable methods of producing ammonia.

In answering this question you may need to use the following relationships and constants

$\Delta G^{\ominus} = \Delta H^{\ominus} - T\Delta S^{\ominus}$

$\Delta G^{\ominus} = -nFE^{\ominus}_{cell}$

where:

n is the number of electrons transferred in the equation for the cell reaction

F is Faraday's constant (the charge carried by a mole of electrons), which is equal to 9.65×10^4 C mol^{-1}

$E^{\ominus}_{cell}$ is the electrochemical cell potential, in volts (1 V = 1 J C^{-1})

$Q = It$

where:

Q is the electric charge, in coulombs

I is the current, in amperes

t is the time, in seconds

1 tonne = 1×10^6 g

One recently published approach to making ammonia uses the following three-step method:

Step 1 Electrolysis of molten lithium hydroxide at 750 K to form lithium metal

$$4LiOH \rightarrow 4Li + 2H_2O + O_2$$

Step 2 Reaction of lithium metal with nitrogen to form lithium nitride

Step 3 Reaction of lithium nitride with water to re-form lithium hydroxide and ammonia

Thus the lithium hydroxide formed in **Step 3** can be re-used in **Step 1** and the process can be repeated.

(a) State the two half-equations that combine to give the overall equation in **Step 1**.

The table below gives the thermochemical data (to 3 significant figures) for **Step 1**.

At 750 K	LiOH	Li	H_2O	O_2
$\Delta_f H^{\ominus}$ / kJ mol^{-1}	–446	+15.0	–268	+15.8
$S^{\ominus}$ / J K^{-1} mol^{-1}	+128	+63.7	+224	+236

(b) Calculate the following for **Step 1** at 750 K.

(i) $\Delta H^{\ominus}$ in kJ mol^{-1}

(ii) $\Delta S^{\ominus}$ in J K^{-1} mol^{-1}

(iii) $\Delta G^{\ominus}$ in kJ mol^{-1}

The electrolysis will only proceed at an appreciable rate when the applied potential exceeds the electrochemical cell potential by 0.60 V.

(c) Calculate the minimum potential that should be applied in **Step 1**.

(d) Write down the equations for **Step 2** and **Step 3** and hence calculate the stoichiometric ratio between the lithium produced in **Step 1** and the ammonia produced in **Step 3**.

In a small-scale experiment, the researchers applied a current of 0.200 A for 1000 seconds. The yield of lithium production in this process was 88.5%. The yield of **Steps 2** and **3** can be assumed to be 100%.

(e) Calculate the mass of lithium generated in **Step 1**.

(f) Calculate the volume of ammonia produced in cm^3 at room temperature and pressure.

A potential application of this approach is to use renewable energy sources as the source of electricity for the electrolysis and to produce ammonia at a farm where it can be used straight away. The average size of a UK farm is 130 acres and a farm requires 0.0770 tonnes of ammonia per acre annually.

(g) If the lithium hydroxide was not recycled at the end of the process, calculate the total mass of lithium (in tonnes) that would have to be produced to generate the required mass of ammonia for a year.