Háskólinn í Reykjavík

Varmafræði

Hópverkefni 1
Orkuskipti og rafeldsneyti

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1 Introduction

Today, most cars use diesel or gasoline, which results in a lot of carbon emission. Because of that, reducing fossil fuel usage is one of the main keys to reach climate neutrality. Many options are being explored in the world, but two of the most popular are using battery powered vehicles (EV) and e-fuel in the form of hydrogen, ammonia or methanol.

This changing process will need a big increase in electricity production, both to power EV's and to make the e-fuel. Following that, a very big factor for many people is the cost. For the change to be viable, it has to be cost-effective.

The goal of this project is to estimate the energy required for Iceland to transition from fossil fuel to different e-fuels and to do a cost estimation of each of the fuels.

2 Energy needs

2.1 Fuel usage

For this project, we will be looking at cars, ships and aviation in Iceland. To start of, we have to set our base for the calculations by defining the fuel usage in each sector. For our calculations, we will assume that the fuel is only diesel and that it has the combustion value and efficiency of diesel.

For aviation and ships, since no source was found on how much fuel they consume, we will take a look at oil sale in Iceland. Data from Orkustofnun on how much fossil fuel has been sold in Iceland gives us a good estimation on how much fuel was used. We will assume that every sold ton of oil was actually used and did not go to waste.

Table 1: Tons of oil sold in Iceland by sector and year [1]

Year	**Ships [tons sold]**	**Aviation [tons sold]**
2019	243.701	312.117
2020	190.861	87.061

We can see that in 2020 (and the same applies for 2021) the oil sale in each category dropped by a lot. This was due to the COVID-19 pandemic but the sector most impacted was aviation, where the sale dropped by roughly 70%. For this project, we will therefore do our calculations based on the year 2019.

Now we will take a look at the fuel usage of cars in 2019. We will split the cars into two subcategories, private cars and transportation cars. Since we have a reliable source for how much on average each category drives a year, we can calculate the total fuel usage.

$$\text{Liters used} = \frac{\text{average km}}{year} * \frac{\text{average L}}{km} * \text{amount of cars} \tag{1}$$

Equation 1 gives us how many liters on average are used each year. For private cars we will assume that the average liters of oil used per km are 0,071 [2] and for transportation cars the value is 0,35 [3].

Now to find the total mass used by the cars we use:

$$m = \frac{V}{v} \tag{2}$$

Equation 2 gives us the total amount of diesel used in kg. For the equation, we will assume that the oil (diesel) used is of European standard (EN 590 Diesel) and that the specific volume is $v = 1,180m3/ton = 1180L/ton$ [4].

Using equations 1 and 2 and the assumptions above, we obtain the total amount of diesel used in tons. Since we have transportation cars as one category instead of 5, we calculate the average km/year by doing a weighted average. The weighted average calculated for the transportation cars was 17.050 km/year.

Table 2: Total fuel usage for cars in Iceland in 2019 [5]

	Private cars	**Transportation cars**
Average km/year	12.781	17.050
Average L/km	0,071	0,35
Total cars	269.825	44.965
Liters used	2,45*10^8	2,68*10^8
Tons used	207.627	227.397

Finally, we can summarize every sector together and we obtain the assumed total fuel usage in Iceland in 2019.

Table 3: Total fuel usage for the 4 sectors in Iceland in 2019

	Oil used [tons]
Private cars	207.627
Transportation cars	227.397
Ships	243.701
Aviation	312.117

2.2 Heat released and mechanical energy

Now we will estimate how much heat is released through combustion of the fuel and how much mechanical energy is delivered to the vessels. We will assume that the combustion value of diesel is $HV = 46MJ/kg$ [6] and that the efficiency of a diesel engine is 40% [7].

For calculating heat release, we multiply the combustion value with the amount of fuel used.

$$Q = m * HV \tag{3}$$

Equation 3 gives the heat released in joules. Using equation 3 and the data from table 3 we can calculate the heat released in each sector, by multiplying the efficiency with the heat released.

Table 4: Total heat release in each sector and the overall total

	Mass [kg]	**Heat value [MJ/kg]**	**Heat released [MJ]**
Private cars	207.627.000	46	9,55*10^9
Transp. cars	227.397.000		1,05*10^10
Ships	243.701.000		1,12*10^10
Aviation	312.117.000		1,43*10^10
Total	990.842.000		4,56*10^10

Since the efficiency of a diesel engine is assumed to be 40%, we get how much mechanical energy is delivered to the vessels of the cars by calculating:

$$\mathrm{ME} = Q * \eta \tag{4}$$

Equation 4 gives the mechanical energy in joules. We then obtain, by using the total value from table 4 and equation 4, the total mechanical energy that is delivered to the vessels.

Table 5: Amount of energy that is transfered to the vessels in the form of mech. energy

	Heat released [MJ]	**Mechanical energy [MJ]**
Private cars	9,55*10^9	3.82*10^9
Transp. cars	1,05*10^10	4,20*10^9
Ships	1,12*10^10	4,48*10^9
Aviation	1,43*10^10	5,72*10^9
Total	4,56*10^10	1,82*10^10

2.3 Energy - from powerplant to a car

Getting energy that is made in a power plant to a car is a long process. A lot of energy gets lost due to different efficiencies in the process. We will now look at two scenarios. The process of getting the energy to a EV and the process of getting the energy to a hydrogen fueled car. For both scenarios, we assume that the efficiency of transportation of electricity from the power plant to a charging station is 98% [8].

2.3.1 Electric vehicle

Electric vehicles' energy source is the battery. The efficiency of charging the battery can vary between 70% and 90%. We will assume that the efficiency of this process is 80% [9]. After that, the energy in the battery is converted into mechanical energy. The efficiency of this process is about 77% [10]. Using this we obtain that the total efficiency of the process, power plant to mechanical energy in a battery EV, is:

$$\eta_{total} = 98\% * 80\% * 77\% = 60\% \tag{5}$$

2.3.2 Hydrogen car

Fuel cell electric vehicles are powered by hydrogen. They produce no tailpipe emissions, since they only emit water vapor and warm air [11]. The big downside of hydrogen powered cars is that they are not very efficient when storing and moving energy. After moving the electricity from the power plant, hydrogen is separated from water. That is how hydrogen is made (electrolysis). The efficiency of this process is around 60%. After this the hydrogen is condensed, with efficiency of 90%. That is how the hydrogen is stored. After that, when the hydrogen is needed to power the vehicle, a fuel cell is used to turn it back into electricity. The efficiency of that is 40%. Finally, the electricity goes through a motor and is made into mechanical energy, with efficiency of 90% [12]. Using this we obtain that the total efficiency of the process, power plant to a hydrogen car, is:

$$\eta_{total} = 98\% * 60\% * 90\% * 40\% * 90\% = 19\% \tag{6}$$

2.4 Electric energy needed to replace fossil fuel - 3 scenarios

Now, using the data from sections 2.2 and 2.3, we can calculate how much electric energy is needed to replace the fossil fuels. We will assume three scenarios; all sectors use e-fuels, all sectors use batteries (EV) and private cars use batteries and the rest goes for e-fuels.

Since we have found how much mechanical energy is needed for each sector (2.2) and we have calculated the total efficiency (2.3) of getting the energy from a power plant to a car, we can calculate the energy needs by doing:

$$\mathrm{ME}_{needs} = \eta_{total} * E_{total} \tag{7}$$

Which also gives us

$$E_{total} = \frac{\mathrm{ME}_{needs}}{\eta_{total}} \tag{8}$$

Where E_{total} is the total energy we need to fulfil the sector's mechanical energy needs, which is symbolized as ME_{needs}.
We will convert MJ to TWh by dividing the MJ value by $3,6 * 10^9$ seconds.

2.4.1 Scenario 1: All sectors use e-fuels

Equation 6 gives us that the total efficiency of getting energy from a power plant to mechanical energy in a hydrogen vehicle is 19%. Using that, we can calculate the energy needs for each sector by using equation 8 and the data from table 5.

Table 6: Total energy needed if all sectors were hydrogen fueled, in MJ and TWh

	Total energy needed [MJ]	**Total energy needed [TWh]**
Private cars	2,01*10^10	5,58
Transp. cars	2,21*10^10	6.14
Ships	2,36*10^10	6,56
Aviation	3,01*10^10	8,36
Total	9,59*10^10	26,64

2.4.2 Scenario 2: All sectors use batteries for storage

Equation 5 gives us that the total efficiency of getting energy from a power plant to mechanical energy in a EV is 60%. Using that, we can calculate the energy needs for each sector by using equation 8 and the data from table 5.

Table 7: Total energy needed if all sectors were EV, in MJ and TWh

	Total energy needed [MJ]	**Total energy needed [TWh]**
Private cars	6,37*10^9	1,77
Transp. cars	7,00*10^9	1,94
Ships	7,47*10^9	2,08
Aviation	9,53*10^9	2,65
Total	3,04*10^10	8,44

2.4.3 Scenario 3: Private cars use batteries and the rest goes for e-fuels

Now we will use equation 5 (EV) for the efficiency for private cars, 60%, and equation 6 for the other sectors (Hydrogen - H), 19%. Using that, we can calculate the energy needs for each sector by using equation 8 and the data from table 5.

Table 8: Total energy needed if private cars were EV and the rest hydrogen fueled

	Total energy needed [MJ]	**Total energy needed [TWh]**
Private cars (EV)	6,37*10^9	1,77
Transp. cars (H)	2,21*10^10	6,14
Ships (H)	2,36*10^10	6,56
Aviation (H)	3,01*10^10	8,36
Total	8,22*10^10	22,83

2.5 Additional electricity production

The by far two largest energy sources in Iceland are hydro- and geothermal power plants. In table 9, data from Orkustofnun shows how other sources are almost irrelevant in comparison to hydro and geothermal energy.

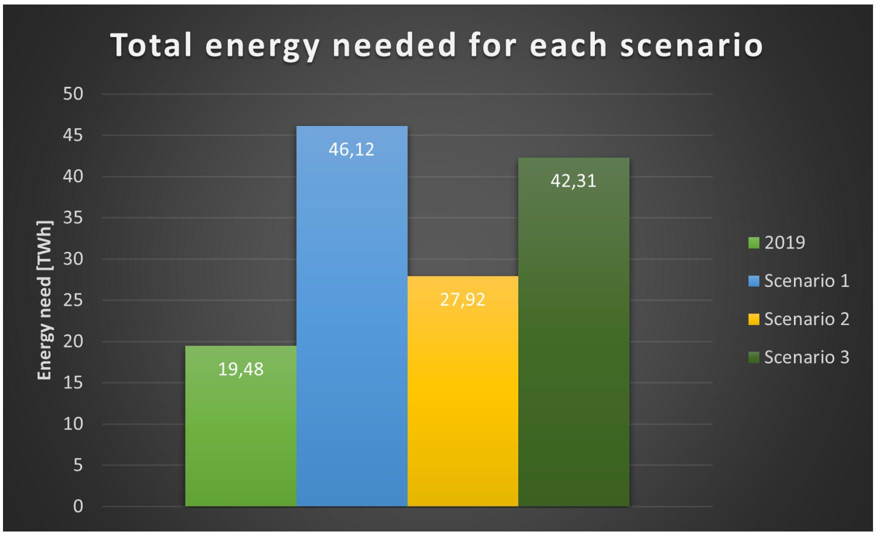
Table 9: Iceland's electricity production by source in 2019 [13]

Source	Electricity production [TWh]
Hydro	13,46
Geothermal	6,01
Wind	0,0066
Fuel	0,0027
Total	19,48

Using the total numbers from tables 6-8 we can compare and see how much electricity production would need to be increased to meet the demand for energy. For each scenario, we calculate the total electricity production needed as the 2019 production total plus the total values from tables 6-8.

Table 10: The additional electricity production needed for the scenarios

	Electricity production [TWh]	Increase from 2019
2019	19,48	x
Scenario 1 - total	46,12	136,76%
Scenario 2 - total	27,92	43,33%
Scenario 3 - total	42,31	117,20%



Graph 1: Total energy production needed for each scenario

3 Cost comparison

3.1 HHV and LHV for hydrogen

The heating value of a substance is the amount of heat released during the combustion of a specified amount of it.

The lower heating value (LHV) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered [14].

The higher heating value (HHV) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products [14].

Table 11: HHV and LHV of hydrogen [14]

	HHV [MWh/kg]	**LHV [MWh/kg]**
Hydrogen	0,0394	0,0334

3.2 Electric energy needed to produce 1 kg of hydrogen

Now we will look at how much energy is needed to produce 1 kg of hydrogen. Like in chapter 2.3.2 we will assume that the efficiency for electrolysis is 60%. From table 11 we get that a completely efficient electrolysis system would require 0,0394 MWh of electricity to produce 1 kg of hydrogen. To calculate the total energy needed we use equation 8 which gives:

$$E_{total} = \frac{0,0394 \text{ MWh/kg}}{0,60} = 0,066\frac{MWh}{kg} \tag{9}$$

3.3 Cost to produce 1 MWh of hydrogen

Now we look at how much it costs to produce 1 MWh of hydrogen. We will assume 3 different price levels of energy cost and that other cost is $45/MWh.

Table 12: Energy cost for the different price levels

	Energy cost [USD/MWh]
Level 1	60 + 45 = 105
Level 2	45 + 45 = 90
Level 3	30 + 45 = 75

The usable energy in hydrogen is 0,0336 MWh/kg [15]. That gives us that the amount of hydrogen needed for 1 MWh of usable energy is:

$$m = \frac{1MWh}{0,0336MWh/kg} \approx 30kg \tag{10}$$

Using the energy needed for 1 kg of hydrogen in equation 9, 0,066 MWh/kg, gives us the cost for 1 MWh of hydrogen by doing:

$$cost = \frac{USD}{MWh} * \frac{MWh}{kg} * \text{ usable kg} \tag{11}$$

Now we can calculate this for each level in table 12 by using equation 11 and values stated above.

Table 13: Total cost to produce 1 MWh of hydrogen

	Total cost [USD]
Level 1	207,9
Level 2	178,2
Level 3	148,5

3.4 Liters of gasoline needed to produce 1 MWh of heat

Now we will take a look at gasoline as fuel and how many liters of it are needed to produce 1 MWh of heat. To calculate the volume, we can put equations 2 and 3 together and we get the volume needed.

$$V = \frac{Q * v}{\text{HV}} \tag{12}$$

Equation 12 gives us the volume in L. We will assume that for gasoline, the specific volume is $v = 1,4m^3/ton = 1,4L/kg$ [4] and the combustion value is $HV = 45MJ/kg$ [6]. We then obtain the liters of gasoline needed to produce 1 MWh of heat is:

$$V = \frac{1 \text{ MWh} * 1,4\frac{L}{kg}}{45\frac{MJ}{kg} * \frac{0{,}000278 \text{ MWh}}{1 \text{ MJ}}} = 111,9 \text{ L} \tag{13}$$

We showcase the full formula for a better understanding of how the units cancel out to obtain liters.

3.5 Liters of gasoline needed to travel 100 km

Now we will look at how many liters of gasoline are needed, on average, to travel 100 km and how many MWh that entails. The average amount of liters per 100 kilometers for new 2020 model cars, light trucks and SUVs is 9,3 L/100 km [16]. From equation 13 we know that 1 MWh equals 111,9 liters of gasoline. We then know that 1 liter gives us:

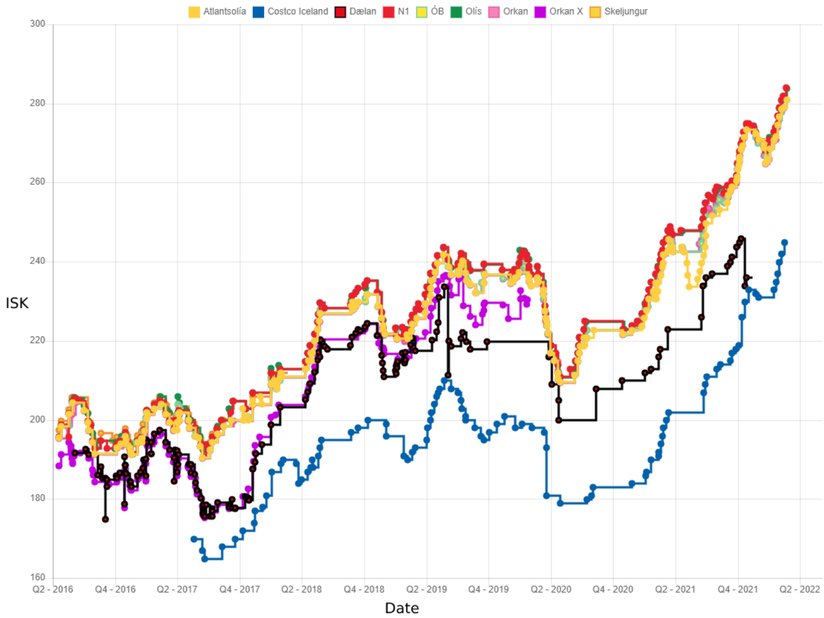
$$\frac{1 \text{ MWh}}{111,9L} = 0,008937\frac{MWh}{L}$$

To drive 100 km with the average 9,3 L/100km we thus need:

$$9,3 \text{ L} * 0,008937\frac{MWh}{L} = 0,083 \text{ MWh}$$

3.6 Gasoline price in Iceland

Gasoline prices in Iceland have gone up a lot lately. The average price of the main gasoline retailers in Iceland is about 275 ISK/liter [17]. In 2019, the gasoline price in Iceland was around 202 ISK/liter. These high prices are partly due to the high taxes that the Icelandic government puts on gasoline. The taxes on gasoline are; oil tax, carbon tax, and VAT. Overall, the government gets about 139,25 ISK/liter [18].



Graph 2: Gasoline prices from the main retailers in Iceland from 2016-2022 [19]

Using 9,3 L/100 km we obtain that the current cost of driving 100 km is:

$$9,3\frac{L}{100\text{km}} * 275\frac{ISK}{L} = 2557,5\frac{ISK}{100\text{ km}} \tag{14}$$

3.7 Cost of driving on hydrogen

Now we will calculate the cost to drive 100 km if the fuel used would be hydrogen, based on the prices from table 13. We will assume that the hydrogen has the same efficiency as the gasoline, i.e. to drive 100 km we need 0,083 MWh. We will also use the value from equation 10, the amount of hydrogen required for 1 MWh of usable energy, m = 30 kg. We then have the amount of hydrogen we need to drive 100 km:

$$0,08311 \text{ MWh} * 30\frac{kg}{MWh} = 2,49kg \tag{15}$$

Now we can use equation 11 to calculate the cost to drive 100 km on hydrogen for each level in table 13, but instead of m = 30 kg we have m = 2,49 kg.

Table 14: Total cost for each level to drive 100 km on hydrogen

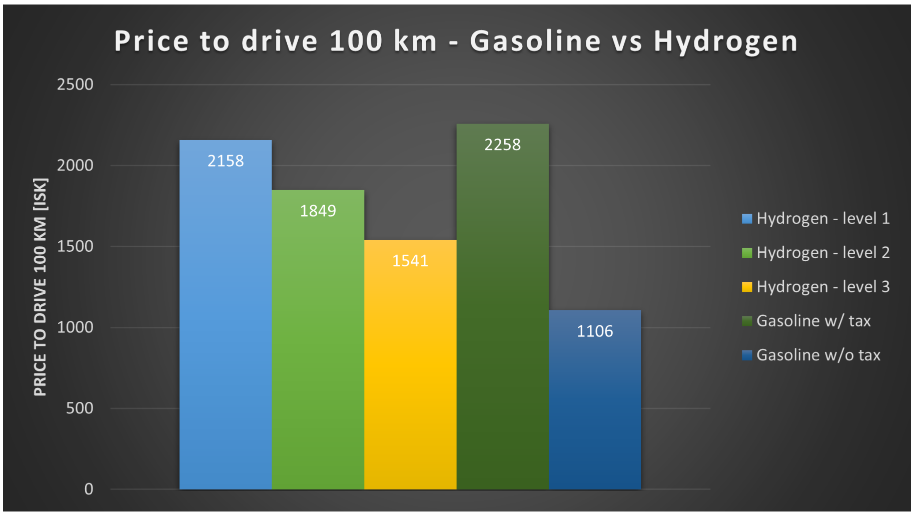
	Total cost [USD]
Level 1	17,26
Level 2	14,79
Level 3	12,33

3.8 Hydrogen vs Gasoline - price comparison

To compare the prices of the hydrogen and the gasoline for driving 100 km, we will first convert the hydrogen price in USD to ISK. We will use the price 1 USD = 125 ISK. Table 14 gives us the hydrogen price for 3 levels and equation 14 gives us the gasoline price (with taxes). Section 3.6 gives us that the taxes make up 51% of the gasoline price.

Table 15: Price comparison for driving 100 km on hydrogen and gasoline

	Price [ISK]
Hydrogen - level 1	2158
Hydrogen - level 2	1849
Hydrogen - level 3	1541
Gasoline w/ tax	2258
Gasoline w/o tax	1106



Graph 3: Gasoline vs Hydrogen prices for driving 100 km

Graph 3 shows a visual comparison off the hydrogen price versus the gasoline price. To compare the hydrogen price to the gas price with tax is not a fair comparison, since hydrogen would most likely be taxed if it were to replace gasoline. From the graph, we can therefore assume that the price to drive 100 km is very similar for both fuels.

3.9 Cost of driving EV

Finally, we will take a look at the price of driving a EV. Now we will assume that the energy needed to drive 100 km on a typical EV is 15 kWh [20].

Table 16: The consumer price for electricity at Veitur [21]

	Total [ISK/kWh]	**Total with 24% VAT [ISK/kWh]**
Energy price	6,63	8,22

Using that EVs can drive 100 km per 15 kWh and the price from table 16 we get the total price, with tax:

$$15 \text{ kWh} * 8,22\frac{ISK}{kWh} = 123 \text{ ISK} \tag{16}$$

Comparing this value to graph 3, we see that the EV price is by far the cheapest, even though taxes are included.

3.10 Ammonia or Methanol

Since hydrogen is a light molecule, it is very hard to compress, store and transport. For instance, like in section 2.3.2 the process of storing hydrogen and then turning it back into electricity is not very efficient. A lot of energy gets lost in the process, which makes the total efficiency of hydrogen very low. Two alternatives that would be more realistic to use are ammonia and methanol.

Ammonia has 1.5 times higher energy density (12.7 MJ/liter) than liquid hydrogen (8.5 MJ/liter) which makes it easier to store and to transport, i.e. it is more efficient than hydrogen. Because of that, ammonia will be cheaper than hydrogen because a lot less energy will get lost. Also, the boiling point of ammonia, which is -33.4°C versus the boiling point of hydrogen that is -252.87°C, makes it way easier to store than hydrogen since fuels with a low boiling point are very flammable. Because of that, we can assume that the total cost of making and storing ammonia will be way lower than the cost for hydrogen [22].

The same goes for methanol, it is a high density (15,9 MJ/liter) energy carrier which is liquid at atmospheric pressure. That makes it more efficient than hydrogen. Also, it's cost-effective to refuel and store, especially in large volume. On top of that, methanol is also a very high octane fuel, which makes it more efficient than for example hydrogen [23].

4 Conclusion

In this assignment, we calculated the energy needs for Iceland if it were to exchange fossil fuels used in vehicles for electric fuel in the form of batteries and e-fuel. First, we found that the mechanical energy needed to power all vehicles in Iceland in the year 2019 was $1,82 * 10^10$ MJ. After that, three scenarios were examined; 1. All sectors use e-fuels. 2. All sectors use batteries for storage. 3. Private cars use batteries and the rest goes for e-fuels. The efficiencies to power electric- and hydrogen vehicles were calculated as 60% and 19% respectively. Using that, the total energy that Iceland needs to produce to make it viable was found.

Table 17: From section 2, total electricity production needed for each scenario

	Electricity production
2019	19,48
Scenario 1	46,12
Scenario 2	27,92
Scenario 3	42,31

For the second part of the assignment, a cost estimation for different scenarios was made. Three different price levels were found to produce 1 MWh of hydrogen. They were $207,9, $178,2 and $148,5. After that, a comparison was made of how much the cost to drive 100 km was with different fuels.

Table 18: from section 3, price comparison for driving 100 km on hydrogen and gasoline

	Price [ISK]
Hydrogen - level 1	2158
Hydrogen - level 2	1849
Hydrogen - level 3	1541
Gasoline w/ tax	2258
Gasoline w/o tax	1106
EV w/ tax	123

The final result is that there are a lot of viable options for switching to fossil fuel. The cost for hydrogen is very similar to gasoline, but EVs are the cheapest option. The big problem is mainly how all the energy will be made, since Iceland's electricity production will need to be increased by a lot. Iceland is in a very good position worldwide with energy production, so it should be doable. We therefore conclude that fossil fuel is not necessary for Iceland.

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