Fjalla Power ltd

In Icelandic: Fjallavirkjun hf

Fjalla Glacial River Canyon in July 2017

The Fjalla Power Project in East Iceland

Harnessing the Fjalla Glacial River down to the Flow Valley for electricity production

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1. Glossary

Table 1. Naming convention used in the report; italics is for emphasis.

Icelandic	**English** (*in italics*)	**Notes**
Orkuskipti	*Energy Transition*	
Rammaáætlun	*Framework Plan*	… of Conservation and Energy Utilization
Alþingi Íslendinga	*Icelandic Parliament*	
Askja eldstöð	*Askja Caldera*	
Stuðlagil	*Columnar Canyon*	Located downstream in *Jökla Glacial River*
Fljótsdalsheiði	*Flow Valley Heath*	
Herðubreið	*Herðubreið Mountain*	
Fljótsdalur	*Flow Valley*	
Jökulsá í Fljótsdal	*Flow Valley Glacial River*	
Jökla	*Jökla Glacial River*	Also called "Glacial River at Dal"
Kárahnjúkavirkjun	*Kárahnjúka Power Project*	
Kárahnjúkalón/Hálslón	*Kárahnjúka Reservoir*	
Kárahnjúkastöð	*Kárahnjúka Power Station*	Existing Hydro Power Plant 690 MW
Lagarfossvirkjun	*Lagarfoss Power Station*	Existing Hydro Power Plant 28 MW
Arnardalsá	*Arnardalur River*	
Dettifoss	*Dettifoss Waterfall*	Located downstream in *Fjalla Glacial River*
Kreppa	*Kreppa River*	
Jökulsá á Fjöllum	*Fjalla Glacial River*	
Fjallavirkjun	*Fjalla Power Project*	
Fjallalón	*Fjalla Reservoir*	
Fjallastöð	*Fjalla Power Station*	
Jökulsárgljúfur	*Fjalla River Canyon*	
Vatnasvið Jökulsár á Fjöllum	*Fjalla River Watershed*	
Arnardalsvirkjun	*Arnardalur Power Project*	Former power option in *Fjalla Glacial River*
Helmingsvirkjun	*Helmingur Power Project*	Former power option in *Fjalla Glacial River*

2. Preface

2.1. Climate Change and Energy Transition

In the great environmental push towards reducing the use of fossil fuels and moving towards a more sustainable environment, there has been a huge demand for new natural renewable energy production units.

Recently there has been a lot of discussion about the Icelandic nation's energy issues, mainly in relation to impending climate change.

Energy Transition in all forms of transport is imminent. The Icelandic Parliament has decided and in fact established by law that domestic natural and sustainable energy sources should be used instead of imported fossil fuels.

This energy transition has been called the Third *Energy Transition* in Iceland in reference to the already implemented and active use of renewable geothermal heat for domestic heating and electricity production and the large-scale harnessing of hydropower to produce renewable electrical energy.

Domestic energy production for transport will thus be carbon neutral as follows:

- By 2030: A reduction of 55% from "pre-industrial level" (in fact based on emissions in the reference year of 1990), considering a climate policy in accordance with the Paris Agreement 2015.
- By 2040: Achieve full carbon neutrality without (net) emissions of greenhouse gases.
- By 2050: Independent of fossil fuels.

The reference year of 1990 is important since the capital area of Reykjavík was connected to a geothermal utility in the 1960s with the aim of eliminating the use of imported coal for domestic heating. The benefits it brought about should not be overlooked when assessing Iceland's current position in climate matters.

To a great surprise, in June 2021 the Icelandic Government decided to bring forward the year of net carbon neutrality by 10 years, from 2050 to 2040.

2.2. The need for new power plants that use renewable natural energy.

For this purpose, power plants must be built that use natural geothermal energy for heating purposes and for power production and use river streamflow and wind for power production in a sustainable way.

Available electricity forecasts towards 2050 consider all planned energy exchanges and that the highest forecast for energy exchanges in the period is 24.000 GWh/year, even though technical implementations are not yet available in detail. It is cautiously assumed here that energy transition in transport would be half of that or 12.000 GWh/year by the year 2040.

In Iceland green electrical energy will be produced from natural renewable energy resources in three different ways:

1. Geothermal power plants produce electricity that comes with equal output throughout the year, but levelized cost of energy is relatively high or at around **65 USD/MWh**. The current share of total capacity in Iceland is **25,8%**.

2. Hydroelectric power plants also produce electricity according to market demand throughout the year, which is achieved by operating the associated water reservoirs in a flexible manner. Hydropower levelized cost of energy could be **50 USD/MWh**, but economies of scale could make a big difference in lowering those costs. The current share of total capacity is **71,7%**.
3. Wind turbines produce power in windy weather but come to a stop in calm weather. Then it is necessary to rely on other types of power plants to maintain production, and in that it is usually assumed that the flexible hydropower will participate as much as possible. The production cost of wind energy is estimated to be around **32 USD/MWh**, or significantly less than that of geothermal and hydropower plants. The current share of total capacity is **0,1%**.
4. The rest, or **2,4%** are non-renewable fossil fuel power plants.

The key to the planned energy transition is therefore new hydroelectric power plants but unfortunately there are few options available, mainly due to the restrictions that the policy of strict nature conservation has been driving in recent years and decades.

Research has been conducted for a long time on harnessing the *Fjalla Glacial River* eastwards and down to the *Flow Valley*. This is the ideal option for a hydropower station, given that the river is one of the largest watercourses in the country and the difference in height from there down to the *Flow Valley* is exceptionally large, at around 548 meters.

With this report, attention is drawn to the big step that could be taken in the exploitation of domestic and renewable energy sources by carrying out the *Fjalla Power Project*. The option of attracting foreign capital to the project is presented, as this is an extremely costly project. The guiding principle is to construct the power plant with foreign capital to be able to meet Iceland's climate commitments and at the same time get rid of future fine payments, due to non-compliance that currently seem to be expected.

2.3. The Fjalla Power Project

In the following, we will discuss a new idea for implementing this hydropower in another way that we have called in Icelandic Fjallavirkjun, in English the *Fjalla Power Project*. The associated intake reservoir is therefore called in English the *Fjalla Reservoir*.

Dettifoss Waterfall is considered a particularly beautiful waterfall, the natural wonder of *Fjalla Glacial River* as will be described in more detail later in this report.

A few of the main innovative features of the *Fjalla Power Project* are the following:

1. A production capability of 4000 GWh/year, which is 1/3 of the power generation requirement due to the third *Energy Transition* which is to be, for us concerned, 12.000 GWh/year as previously stated.
2. With a low utilization of 5000 hours/year, the installed power will be 800 MW, which offers particularly good possibilities of co-operation with wind power plants in the country to secure higher level of base power production.
3. The underground tunnel from the *Fjalla Reservoir* towards *Fjalla Power Station* in the *Flow Valley* will be at a considerable depth below the *Flow Valley Heath* and therefore with minimal environmental impact. For general information, the diameter of the *Kárahnjúka power project*'s tunnel is 7,6 m. The highest flow rate is 144 m^3/sec with a corresponding highest water velocity of 3,17 m/sec. A comparable implementation of Fjalla Power Project with a similar result would give a tunnel with a diameter of 8,0 m and a maximum flow of

159 m^3/sec. This means that for *Kárahnjúka Power Project*, water for 2,8 hours of full production is available in the tunnels, but for 4,3 hours in the case of the *Fjalla Power Project*. Of course, this will become clearer in later stages.

4. The *Fjalla Power Project* is very similar to the existing and successful *Kárahnjúka Power Project* (2007) in its entire structure and having the experience as a reference will increase safety measures of the *Fjalla Power Project* in all respect, both during construction and operation. Construction of the *Kárahnjúka Power Project* began in 2002 and the power plant was officially commissioned on November 30, 2007, with a construction period of 5-6 years. There is reason to believe that it could also be the construction period of the *Fjalla Power Project*.
5. An attempt will be made to study the possibility of diverting a part of the overflow of the *Kárahnjúka Reservoir* towards the *Fjalla Reservoir* and even to an increasing extent in cases that *Kárahnjúka Reservoir* closes in with stranded energy during water-rich late summers. This could relieve the overflow down the *Jökla Glacial River*, thus if necessary, protecting the environmentally friendly *Columnar Canyon* and the salmon fishing further downstream. This option needs to be thought through and designed in more detail.
6. We expect to somewhat make it possible to control the flow of the *Fjalla Reservoir* towards the *Dettifoss Waterfall* to create variations in the appearance of the waterfall for visitors and pedestrians. Water takes 12 hours to flow down this path and if it is released from the *Fjalla Reservoir* at midnight, it will appear in *Dettifoss Waterfall* during the next afternoon. This could be designed to enhance the experience down by the waterfall, which some find unsightly with all the mud, although it can hardly be disputed that it looks powerful.

Later in the report those points will be examined in more detail.

The version of the *Fjalla Power Project* that we present in this report is the only significant hydroelectric power plant of this magnitude in sight in Iceland today, and that could be considered viable.

We would like to encourage the Ministry of Energy to take part in increasing the understanding of this option and to consider removing the nature conservation constraints from these natural projects through government actions, including in the Icelandic Parliament. After that, it would be possible to start building and then operating the *Fjalla Power Station*.

It should be noted that this report does not deal specifically with the necessary power lines for the transmission of electricity from the power plant, and it will be left until later.

It could be mentioned that, at this stage, neither the environmental impact of releasing water from *Fjalla Glacial River* to *Flow Valley Glacial River* nor the expected impact on the estuary of the latter major river will be discussed here and now.

In this regard, it is also worth noting that increased water in *Flow Valley Glacial River* gives rise to further expansion of *Lagarfoss Power Station*.

These are projects of later design.

2.4. The *Askja volcano and Herðubreið Mountain*

The *Askja Caldera* is one of the largest calderas in Iceland and is situated in the middle of the Icelandic Highland. The weather seems to be gloomy all the time in the few weeks you can visit without a blanket of snow covering the whole area. The volcano is extremely powerful and dangerous. When it erupted in 1875, the tephra and ash had devastating effects, ruining living conditions in the northeast part of the island and even affecting other Nordic countries and northern Europe which is hard to comprehend since the eruption only lasted a few hours. Since this catastrophic event, eight other eruptions have occurred in Askja in the 20th century, the latest one being in 1961. Fortunately, these eruptions were very small. (Einar Pall Svavarsson, Apr 2022). The risk that might arise if the *Askja Caldera* were to erupt soon is not discussed here, but the *Fjalla Reservoir* is near the volcano, as is the *Kárahnjúka Reservoir*.

The name of the mountain, *Herðubreið*, is named after a large ax made of hardened steel that has stuck in the ground. *Herðubreið* is a 1682 m high tuff mountain north of *Vatnajökull glacer* next to the Askja volcano and within Vatnajökull National Park. She is often referred to as the "Queen of the Icelandic Mountains" as she is considered exceptionally beautiful. In addition, Herðubreið was chosen as Iceland's national mountain in an election in 2002. For a long time, it was considered unclimbable, until 1908.

Neither of these natural formations will be affected by the construction of Fjallavirkjun, but access for tourists and nature lovers will be made easier with new infrastructure projects.

Figure 1. The *Askja Caldera in foreground and Herðubreið mountain in background (*Photo by Ómar Ragnarsson)

3. Introduction

On August 10, 2019, Guðmundur Ingi Guðbrandsson, then the Minister of Environment and Natural Resources, signed the protection of the *Fjalla Glacial River Watershed* in accordance with the Act on Conservation and Energy Utilization *Framework Plan*. This was the first protection of an area in the protection category of the *Framework Plan*. The signing took place in a mountain hut in Ásbyrgi, 30 km downstream from *Dettifoss Waterfall*, and was considered part of the government's efforts in conservation.

With the Act, the river *Fjalla Glacial River* was protected against electricity production. Proposals were then underway for two options, *Arnardalur Power Project* and *Helmingur Power Project*, but the protection covered both of these cases. The *Fjalla Glacial River* will not be affected by the planned *Fjalla Power Project*, other than the fact that the flow will decrease including at *Dettifoss Waterfall*, but not so much that its troll face will be noticeable even in wintertime. The appearance of the waterfall will be controlled with valves in the *Fjalla Reservoir*, which will be remotely controlled from Dettifoss. The water flow takes about 12 hours for flow from the reservoir to reach Dettifoss, but it could be planned by remote control from the waterfall, even in special cases according to wishes of the owners.

This action by the Minister of the Environment received little general discussion at the time, and the main purpose of this report is to try to have the matter taken up again and then with a comprehensive review, with nature conservation, profitability and interests of the Nation as a guide.

4. Former Hydropower options

With *Arnardalur Power Project*, the idea was to construct a 1165 Gl water reservoir by damming *Arnardalur River*. The *Fjalla Glacial River*, *Kreppa River* (semi-glacial) and *Arnardalur River* (mountain river) would flow into the reservoir. From there, activated in two stages down to the *Flow Valley* near the place where the existing *Kárahnjúka Power Station* is located. Energy production capacity was estimated at 3404 GWh/year. With a utilization time of 5800 hours/year, the installed power was estimated at 587 MW.

With *Helmingur Power Project*, There would be a reservoir in the same place but only with capacity of 43 Gl. From there the potential water energy would be harnessed in one phase down to *Flow Valley* in the so called *Helmingur Power Station*. Production capability of electricity was estimated 1525 GWh/year, and with a utilization of 5800 hours/year, the installed power was estimated at 263 MW.

These older ideas have now been rejected by the said nature conservation constraints in the *Framework Plan*.

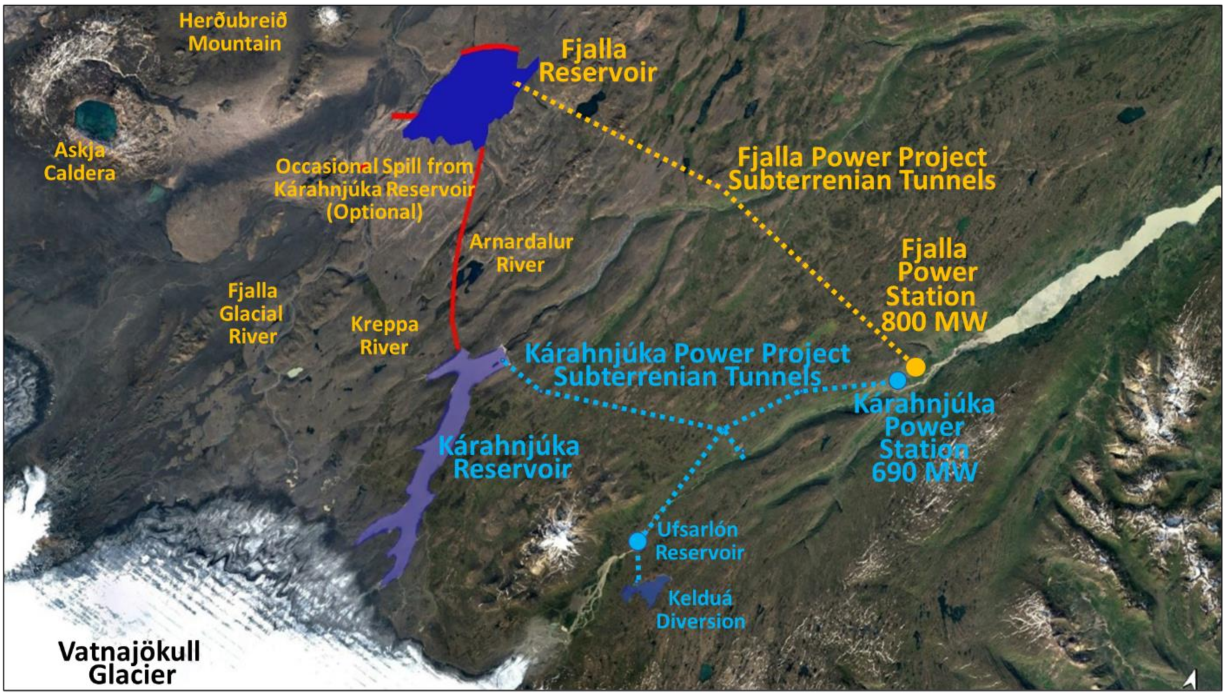
5. The new option – Fjalla Power Project

Figure 2. Overview of the *Fjalla Power Project* in Iceland

Harnessing the energy potential of *Fjalla Glacial River* down to the *Flow Valley* is the biggest untapped hydropower option for power generation in Iceland today. It is hard to see how to achieve the planned *Energy Transition* in transportation without it. The largest current hydropower plant in Iceland is the *Kárahnjúka Power Station* 690 MW.

In this report, a new version of a power plant at the same location is introduced, which has been named the *Fjalla Power Project*.

Figure 3. *Fjalla Power Project*. Main landmarks. Existing structure in blue



Here a 1194 Gl storage capacity is assumed in *Fjalla Reservoir* and the potential energy is harnessed in one phase down to *Fjalla Power Station* in the *Flow Valley*.

The possibility of supplying *Kárahnjúka Reservoir* overflow water to *Arnardalur River* and from there to the *Fjalla Reservoir* would also be examined. *Kárahnjúka Reservoir* stands 77 meters higher than the *Fjalla Reservoir*, which means that it should be easy to establish with a self-flowing channel.

It would also be necessary to examine in more detail whether it is possible to expand even further in size the *Fjalla Reservoir*, so that a significant sharing of water between water-years would be possible. It also opens up the possibility of operating the *Fjalla Power Station* power plant also as a peak power station, and with increased installed power it would then be possible to run the power plants against wind farms all over the country. In terms of energy production, the operation of *Fjalla Reservoir* with storage sharing between years. *Fjalla Power Station* with ample installed power capacity would then become a combination of a base power plant and a top power plant.

6. Guaranteed minimum flow at *Dettifoss Waterfall*

Figure 4 shows an example of how it will be possible to release a wave of water from the *Fjalla Reservoir* and Figure 5 shows how the flow could possibly appear and create a guaranteed flow of 165 m3/sec at *Dettifoss Waterfall*, which is believed to be needed to show the waterfall's full fury. In the example, it is assumed that the flow could last for 1 to 6 hours, but that will depend on the roughness of the waterway from the *Fjalla Reservoir* down to the *Dettifoss Waterfall*. How this will play out in real life will be subject to further research at a later stage.

Figure 4. Example of flow released from the Fjalla Reservoir.

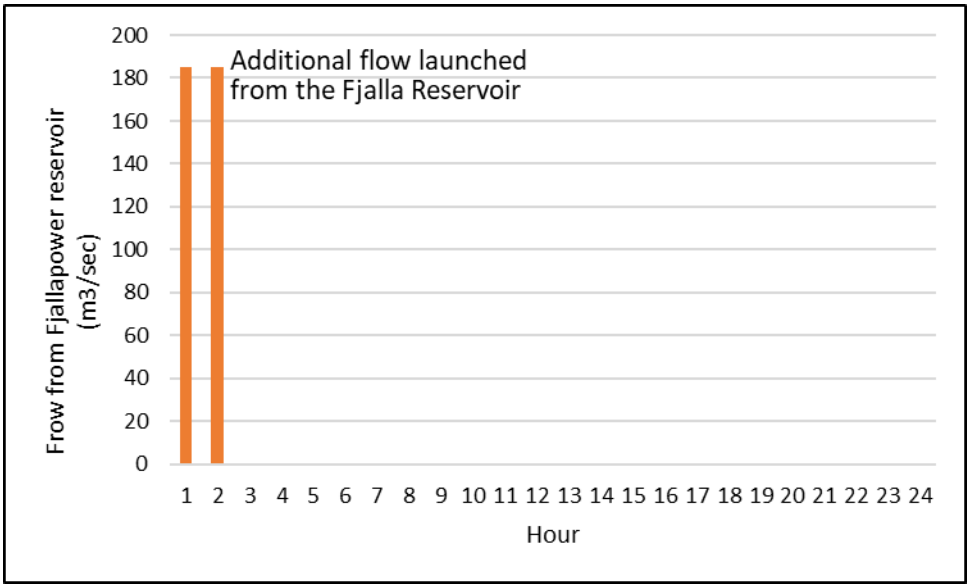
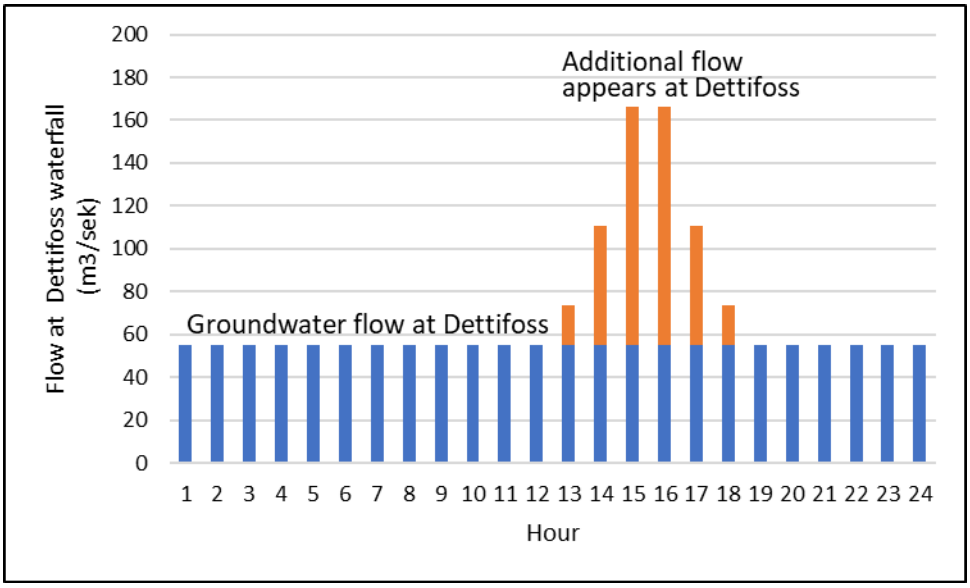


Figure 5. Example of flow from the Fjalla Reservoir received at Dettifoss waterfall.



This model would certainly need further validation.

With an energy price of 40 USD/MWh, which is reasonable, each such splash that bypasses the hydropower production, would be priced at around 45 thousand US dollars, and with the currency rate of 137 ISK/USD at around 6 million ISK. Maybe a sales product is appearing here, but from whom and for whom?

It would be possible to imagine that a certain type of water wave could be ordered from the *Fjalla Reservoir* by the management office at *Dettifoss Waterfall*, but an automatic device with the possibility of remote control would be installed at *Fjalla Reservoir* for that purpose. In this way, equipment would be allowed to develop according to the reactions and wishes of travelers and other visitors.

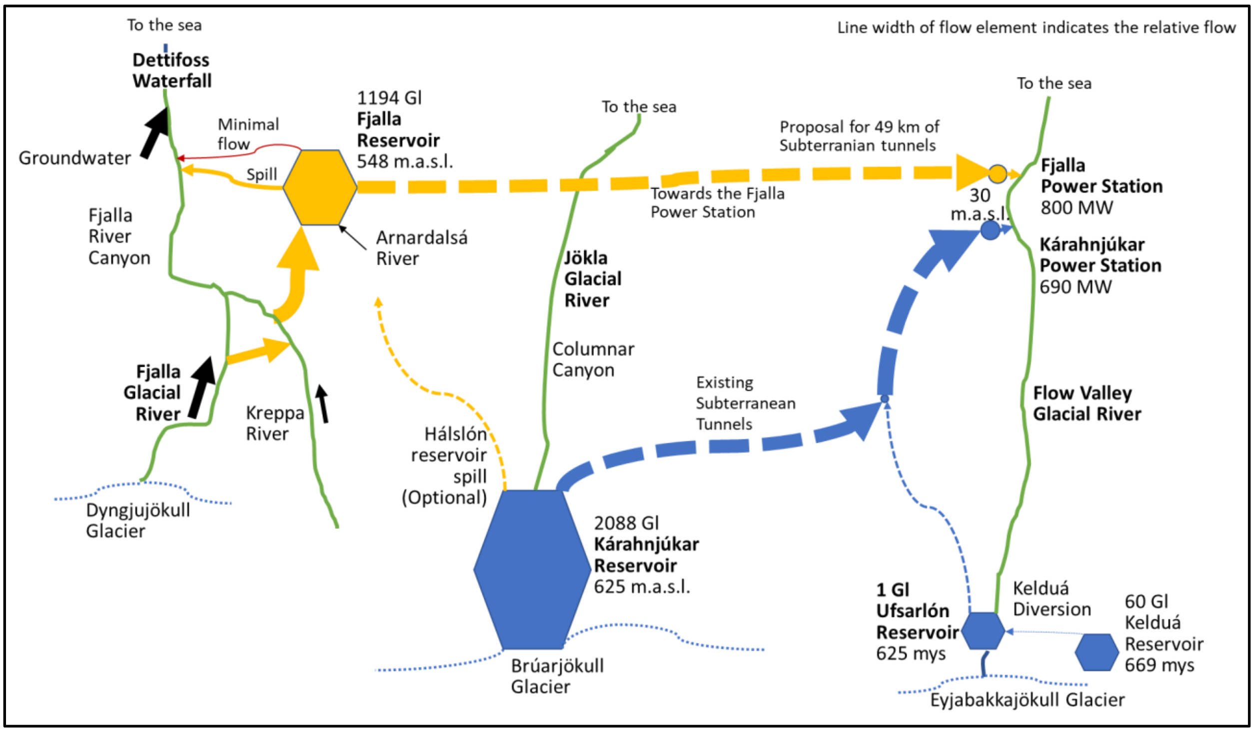
Figure 6. *Dettifoss Waterfall* in summer

Figure 7. *Dettifoss Waterfall* in winter

7. Simulation of Fjalla Power Project

Figure 8 shows in a diagram the arrangement of the proposed *Fjalla Power Project* and the arrangement of the existing *Kárahnjúka Power Project*.

Figure 8. Arrangement diagram of **Kárahnjúka**- and **Fjalla Power Projects**

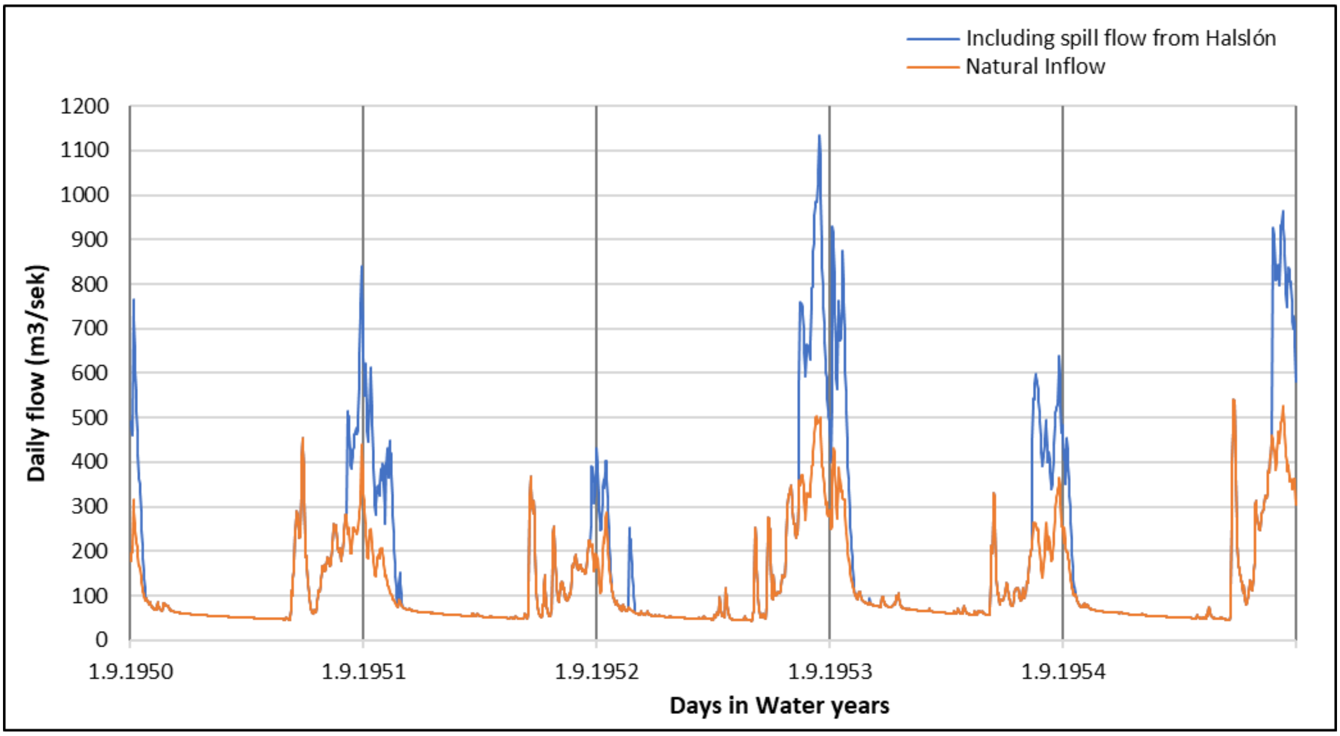


To give a rough idea of magnitudes, the line width of the flow elements is intended to show the ratio of the average flow of the individual flow elements.

The simulation that was performed is not according to the traditional method, where the energy capacity of the power plant is defined as market increase that the interconnected electricity system of the country would handle with the introduction of the power plant. Rather, for simplicity, the production capacity is determined for an infinitely large (imaginary) market. With this approach, it is possible to focus more on the infrastructure of the power plant, which is the main purpose of the initial design stage of the *Fjalla Power Project*. Thereby, it is possible to focus more on the internal structure of the project, without studying how it would fit into the current electricity market and what measures would need to be taken in the transmission system.

Figure 9 shows, as an example, the flow in the first 5 years of the 51-year flow series of the water years 1950-2001. The inflow of *Fjalla Reservoir* which is composed of (*Fjalla Glacial River*) + (*Kreppa River*) + (*Arnardalur River*). In addition, the flow through the spillway in *Kárahnjúka Reservoir* is added stacked, and which is expected to be directed to *Fjalla Reservoir*. The feasibility of that project remains to be verified.

Mynd 9. *Fjalla Reservoir* inflow, stacked diagram.



Note that the unit of flow in the figure is (m^3/sec).

In Figure 10, however, the flow unit is (Gl/day), which is considered a more suitable unit for discussing flow simulations.

1 m^3/sec = 0.0864 Gl/day.

Figures 10 and 11 show, as for figure 9, only the first 5 water years of the total 51 years of model results for the water years 1950/51 to 2000/01 and which were put separately in an EXCEL model made only for the purpose of this observation.

The main purpose of the EXCEL computational model is to calculate electrical power production capability of the project and be able to perform the necessary sensitivity analyses.

Given the inflow as demonstrated in Figure 9, the calculation model disposes of it as Figure 10 shows and which leads to variations in the contents of *Fjalla Reservoir*, as described in Figure 11.

Figure 10. Disposal of water from *Fjalla Reservoir*. Flow unit is (Gl/day).

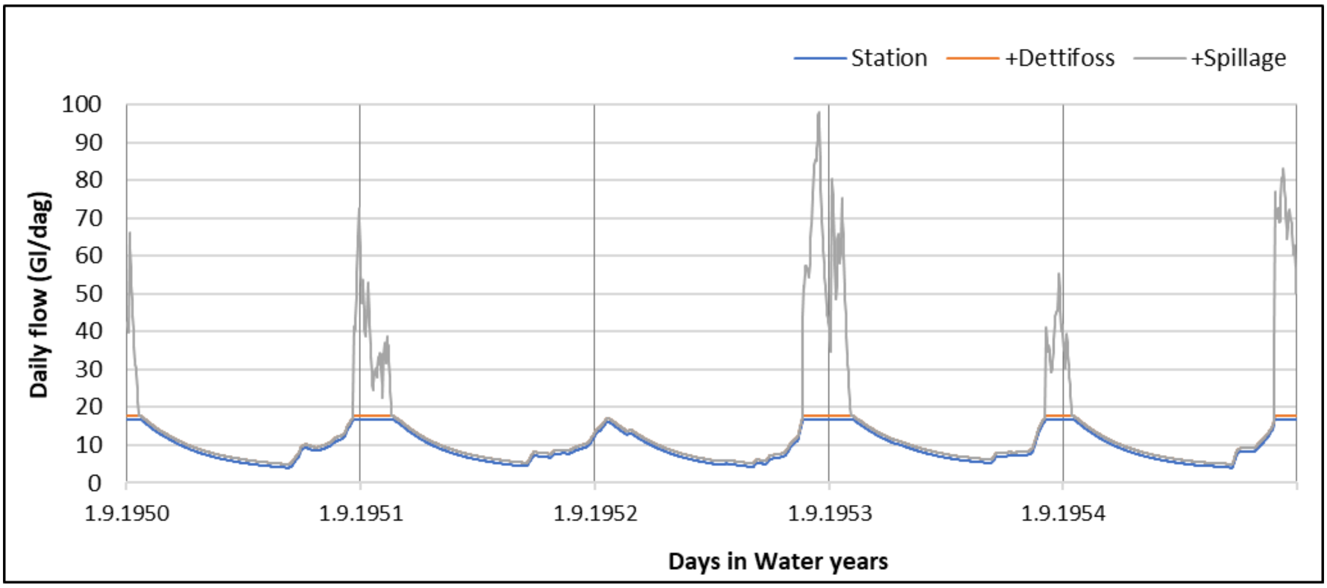


Figure 11. Development of content in *Fjalla Reservoir*. Unit is (Gl).

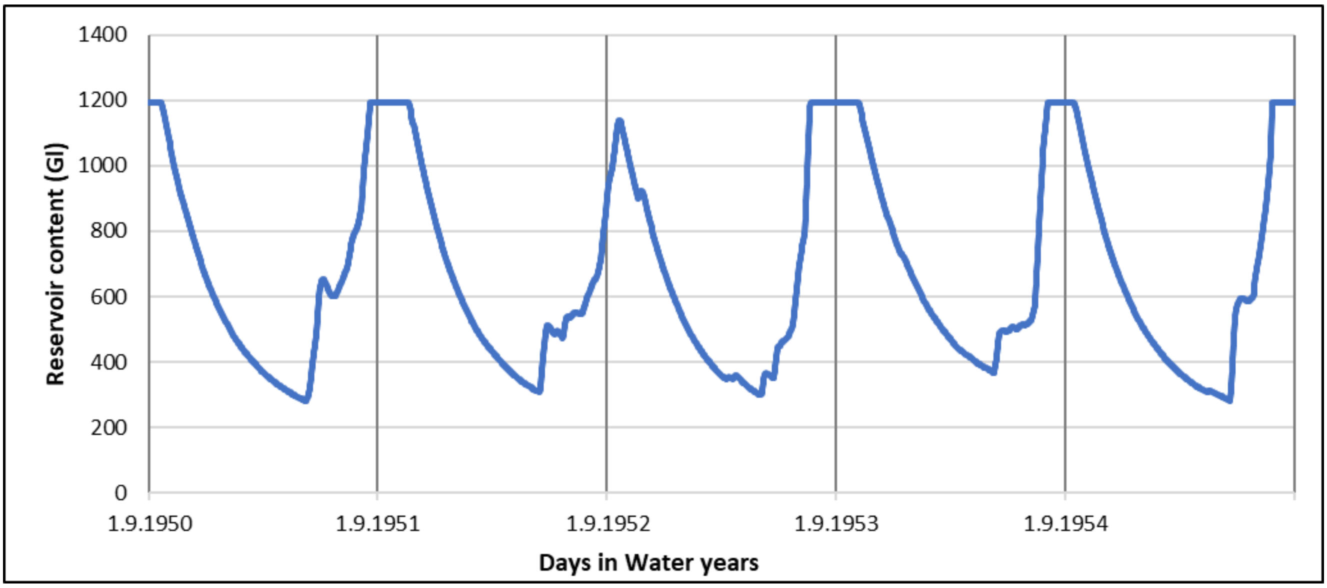


Figure 12 shows in a graph the development of the content in *Fjalla Reservoir* for all the 51 water years of 1950–2000 as reflected in the computer simulation.

Figure 12. *Fjalla Reservoir* simulation results for water years 1950-2000

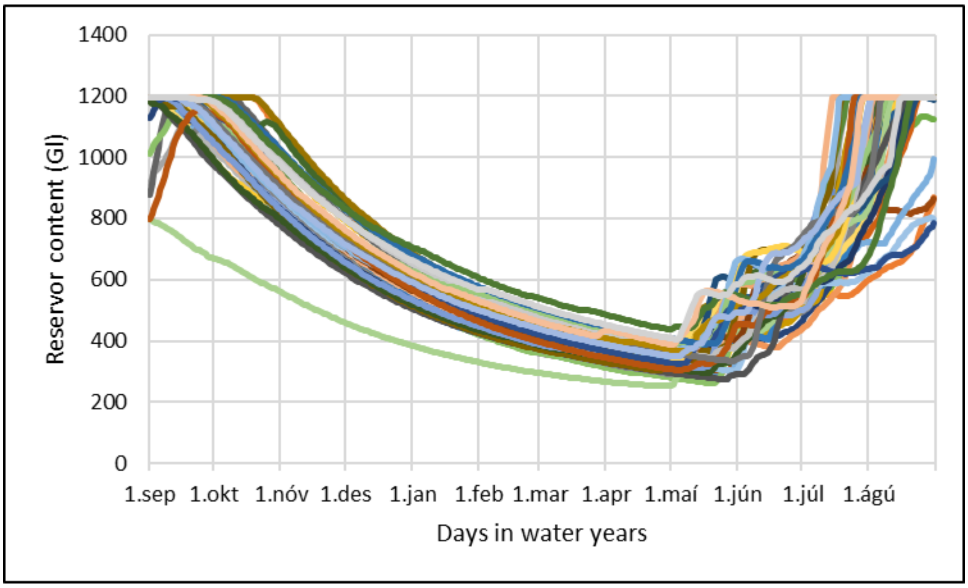
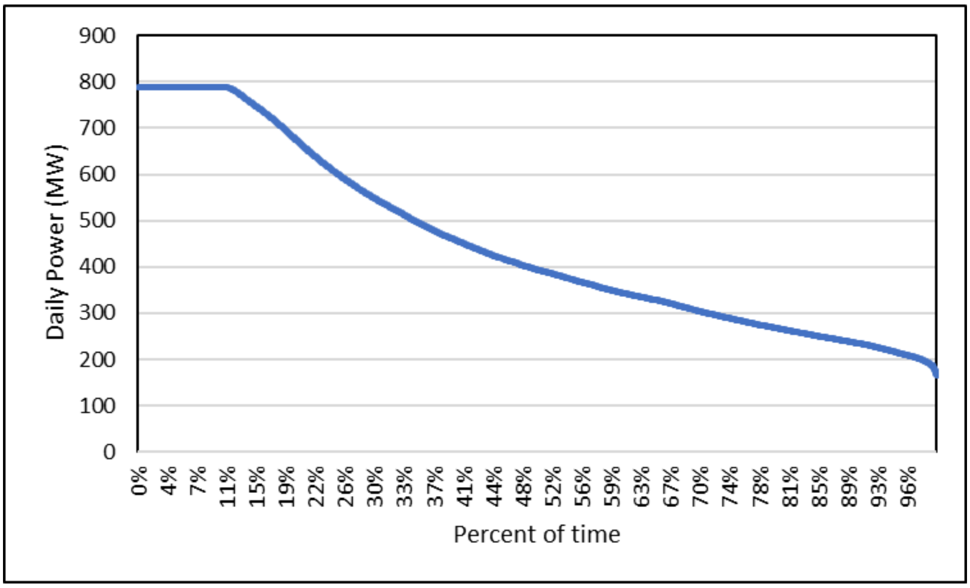


Figure 13 shows in a graph the associated power production of *Fjalla Power Station,*

Figure 13. *Fjalla Power Station* duration curve for water years 1950-2000.



8. Sensitivity analyses

Figures 14 and 15, show in blue color how the annual production changes with two of the most important parameters of hydropower plants. Reservoir size is in (Gl) and installed production capacity in (MW). Also shown in amber color are the selected operating parameters of 1194 Gl reservoir size and 800 MW installed power capacity, which lead to an average annual production capability of 4000 GWh/year for the *Fjalla Power Station*.

Figure 14. *Fjalla Power Station* production and reservoir storage

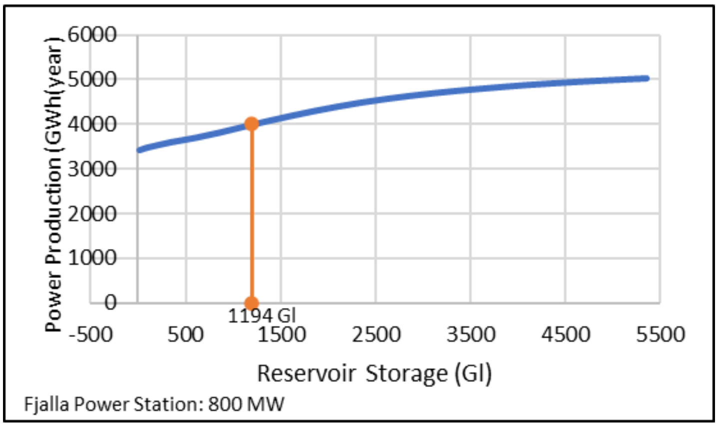
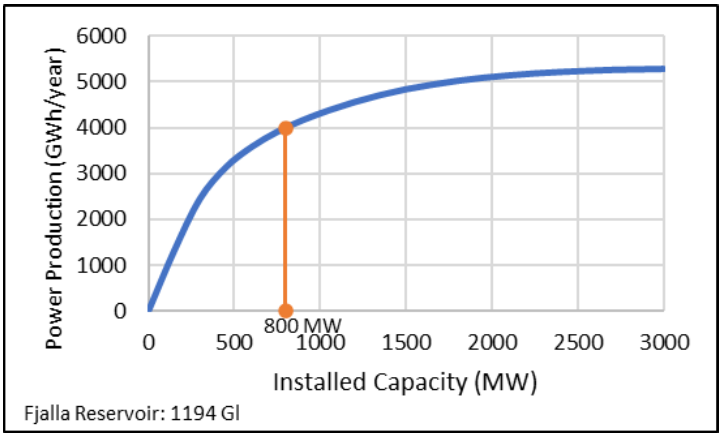


Figure 15. *Fjalla Power Station* production and installed capacity



In the graphs above, the horizontal axes show results for higher values than are realistic, but these need to be re-determined in later stages and during the final design of the power plant.

Another view of this variation can be seen in Table 2, which explains how the production capacity would be with different choices for both the size of *Fjalla Reservoir* and the installed power in *Fjalla Power Station*.

Selected dimensions used in this report, ie 1994 GL size of Fjalla Reservoir and 800 MW installed power in *Fjalla Power Station* are marked separately with boxes in the table.

The cost increase for the expansion of reservoir size and installed power determine in each case which sizes will be finally chosen.

Although we initially chose to target the production capacity of 4000 GWh/year, theoretically according to table 2, it would be possible to it would be possible to achieve a production capability up to 5300 GWh/year, with the choice of a large enough reservoir size and installed power capacity, which would probably be unrealistic due to increase in incremental capital costs.

This will be carefully considered during the final design of the *Fjalla Power Project*.

Table 2 Production capability of the *Fjalla Power Station* in GWh/year.

Fjalla Reservoir (GL)	**Fjalla Power Station Installed Capacity (MW)**										
	0	**200**	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**	**1800**	**2000**
30	0	1701	2514	3034	3444	3782	4055	4298	4493	4658	4798
200	0	1720	2610	3151	3550	3867	4125	4355	4542	4703	4840
400	0	1730	2702	3240	3631	3939	4194	4421	4607	4766	4898
600	0	1735	2775	3321	3708	4019	4274	4498	4682	4833	4958
800	0	1738	2838	3406	3799	4112	4362	4583	4759	4903	5016
1000	0	1741	2893	3494	3900	4212	4456	4671	4838	4965	5065
1194	0	1742	2940	3578	4000	4311	4551	4756	4905	5021	5108
1400	0	1743	2983	3663	4104	4415	4651	4838	4971	5075	5146
1600	0	1744	3019	3741	4198	4513	4738	4908	5031	5118	5179
1800	0	1745	3052	3813	4287	4606	4818	4975	5084	5156	5207
2000	0	1746	3080	3878	4370	4687	4887	5036	5127	5187	5231
2200	0	1746	3105	3937	4448	4760	4953	5085	5162	5215	5253
2400	0	1747	3127	3992	4517	4823	5013	5127	5192	5240	5273
2600	0	1747	3147	4041	4579	4882	5061	5159	5219	5262	5286
2800	0	1747	3165	4086	4635	4936	5100	5189	5244	5279	5293
3000	0	1748	3181	4127	4686	4985	5133	5214	5265	5289	5299

9. Key Features of the Fjalla Power Project

The discussion above shapes ideas for the implementation of a hydroelectric power plant, which is defined in more detail in Table 3.

Table 3. Key Features of the *Fjalla Power Project*

Item	Unit	Fjalla Power	Notes
Average river reservoir inflow (Fjalla Glacial River+Kreppa+Arnardalsá)	m3/sec	127,6	Flow series 1950-2000, 51 water years
Average-spill overflow from Kárahnjúkar Reservoir	m3/sec	30,0	Former result of operation simulations
Average-inflow total per sec	m3/sec	157,6	
Average-inflow total per year	Gl/year	4969	Average of 51 water years
Average daily inflow total	Gl/day	13,6	Average of 51*365 = 18.615 days
Fjalla Reservoir	Gl	1194	For 4000 GWh/year production capability
Tunnel length	km	49	The world's longest hydroelectric tunnel
Level of Fjalla Reservoir	m.a.s.l.	548	m.a.s.l. meters above sea level
Outlet level in Flow Valley	m.a.s.l.	30	
Gross head	m	518	
Tunnel energy losses	percent	10%	Estimated
Net head	m	466,2	
Energy factor	GWh/Gl	1,123	
Inflow potential energy	GWh/year	5582	
Average power production capability	GWh/year	4000	
Utilization of potential energy	percent	72%	
Utilization of installed capacity	hours/year	5000	Equivalent to 57% capacity utilization
Fjalla Power Station installed capacity	MW	800	

Fjalla Power Project would be a key project for strengthening of the energy production system to cope with the Third *Energy Transition* in transport in the coming years and decades, including the support for the continued development of intermittent wind power plants in Iceland.

It is worth mentioning that with reservoir storage within and even between water years in the *Fjalla Reservoir* and the possibility of increased installed power in the *Fjalla Power Station*, a power plant option has been created that is significantly different from the previous design of power plants at this particular location.

10. The *Fjalla Power Station* production cost

In light of insufficient information, it is not possible at this stage to calculate the levelized cost of energy from the *Fjalla Power Station*. However let's try to get a rough picture based on what we currently have in hand.

Our starting point is the aforementioned fact that the *Fjalla Power Project* is similar to the *Kárahnjúka Power Project* in its entire structure. Therefore it is a good idea to base on the actual cost of *Kárahnjúka Power Project* when estimating the capital cost of *Fjalla Power Project*.

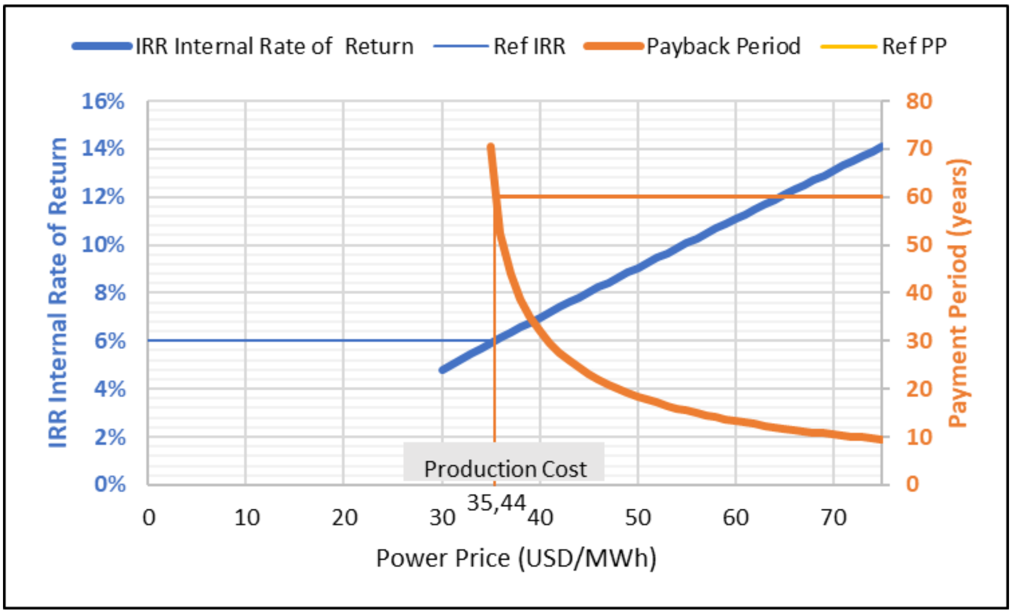
Let's assume an initial capital cost of *Kárahnjúka Power Project* of 146 billion ISK as calculated in 2010. At the price level of the year 2023, that means 233 billion ISK, according to price indexes from the Icelandic Bureau of Statistics. We then increase the cost linearly according to increased installed capacity from 690 to 800 MW. Using currency rates from the National Bank of Iceland results in a capital cost at today price level 1994 million USD. Roughly, the cost estimate for the Fjalla Power Project is then **2,0 billion USD**, where it is assumed that the costs of connecting to the Transmission National Grid will be similar in extent to those of *Kárahnjúka Power Station*.

By assuming 6% interest rate and 60-years payback period for capital costs, an annual cost of operation and maintenance of 0,9% of capital cost, the levelized cost of energy from *Fjalla Power Station* is then estimated at **35,44 USD/MWh** which must be considered a very competitive price. It is appropriate to point out that this is a pure cost price, without any kind of taxes or subsidies.

IRR Internal Rate of Return and PP Payback Period are well-known quantities traditionally used to explain the profitability of projects. The IRR states what interest rate on capital costs of the construction and maintenance & operation of the power plant could support, and the PP explains how long it would take the power plant to pay for itself if all operating surpluses were used to pay off the loans taken out at the beginning of construction.

Figure 16 shows how the IRR of PP would change with the power price of energy from the *Fjalla Power Station*. As shown, and in light of the existing assumptions, you do not want to be getting a lower price than the cost of production.

Figure 16. Sensitivity Analysis of IRR and Payback Period for the *Fjalla Power Station*



For comparision the Levelized Cost of Energy of Landsvirkjun's recent Búðarháls Power Station (2014) 95 MW has been estimated at 35 USD/MWh, i.e. approximately the same price as for *Fjalla Power Station*.

Búðarháls Power Station was built into the Landsvirkjun's infrastructure system in Thjórsá and takes advantage of access to the existing reservoir storage facilities and waterways in the area.

11. More about Fjalla Reservoir

One thing is worth mentioning at this stage, but it concerns the size of the Fjalla Reservoir, which is assumed to be 1194 GL.

Imagine a full Fjalla Reservoir and without further inflow, then if Fjalla Power Station was run at full capacity of 800 MW all the time, the reservoir would drain in 71 days. These hypothetical situations are examined in more detail in Table 4, both for Fjalla Reservoir and other reservoirs in the energy system. The table compares these characteristics of Fjalla Reservoir with other Water Reservoirs in the current national power system.

Table 4. Fjalla Reservoir and comparison with other Water Reservoirs in the national power system

Water Reservoir	Power Station	Part of Iceland	Size (GL)	Energy (GWh)	Drainage (days)	Term of Reservoir
Fjalla Reservoir	Fjallapower	East	1.194	1.361	71	Intermediate
Hálslón+Hraunaveita	Kárahnjúkar	East	2.148	2.975	180	Long
Blöndulón	Blanda	NorthWest	420	287	72	Intermediate
Þórisvatn+Háganga	Vatnsfell	SouthWest	1.834	1.951	135	Long
Krókslón	Sigalda	SouthWest	113	102	5	Short
Sporðalda	Hrauneyjafoss	SouthWest	33	24	2	Short
Ármót	Sultartangi	SouthWest	93	49	3	Short

With reference to Figure 11, it was assumed not to empty The Fjalla Reservoir in the operational simulation, which was made specially for the purpose of this study. It can therefore be cautiously estimated that the joint operation between Fjalla Power Station and the supposed future nearby Wind Farm will be successful, but it will become clearer at a later stage.

12. Fjalla Power Station in co-generation with a Wind Farm

Now it will be examined how much wind power 800 MW Fjalla Power Station with 1194 GL Fjalla Reservoir could conveniently support and the effect of the addition on energy prices from the joint operation as a group.

Figure 17 demonstrates below the blue curve a conventional duration curve for the hydropower and stacked above is the wind power represented by a light brown curve. The actual wind power then lies between the blue and light brown curves.

As stated earlier in this report, 800 MW of installed hydropower in Fjalla Power Station is expected and an additional 854 MW in Wind Power.

It should be noted that the duration curves are created individually and therefore the wind power in a certain period does not match the (as operationally simulated) hydropower in the same period. However, this representation is used here as it leads to a simpler form of diagram, but of course the matter needs to be looked at in more detail at a later stage.

According to this, the average production of Fjalla Power Station will be 457 MW, which is equivalent to the utilization time of 5000 hours/year on an installed capacity of 800 MW.

The average production of 854 MW Wind Power will be 343 MW, which is equivalent to a utilization time of 3500 hours/year.

The premise of this installation is therefore that together the hydropower and the wind power can together provide 800 MW average power every day of the year, which is shown by dotted lines in Figure 17.

Figure 17. Duration curves of Fjalla Power Station's hydropower and associated wind power.

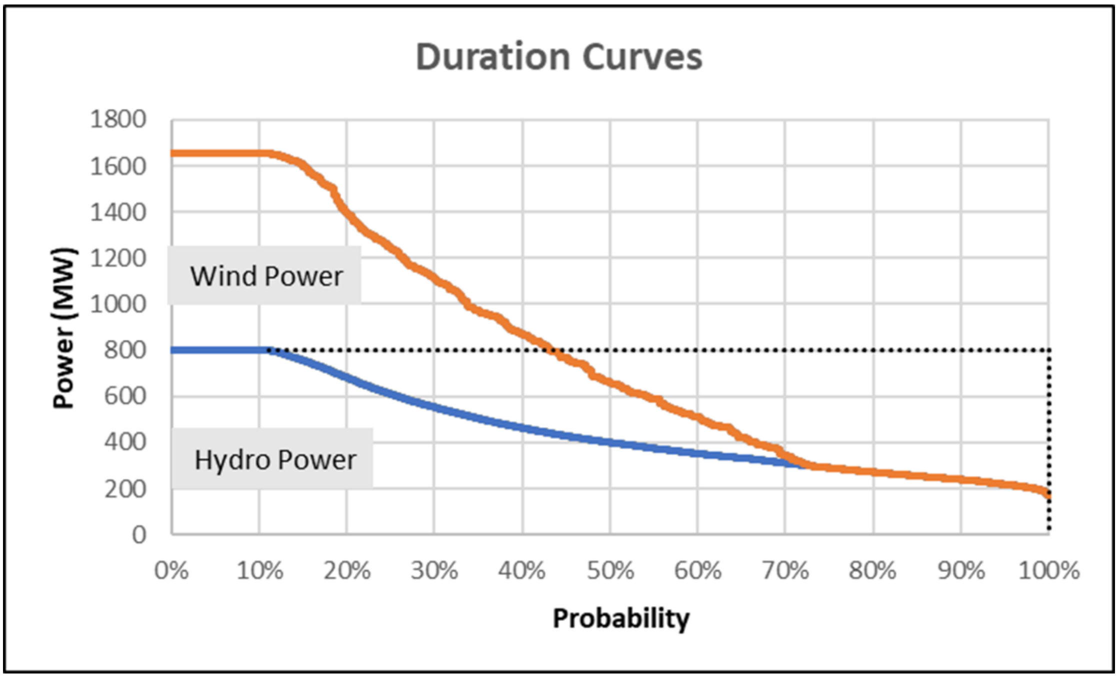


Table 5 calculates the financial viability of a power plant package, which consists of an 800 MW Fjalla Power Station in a joint operation with an 854 MW Wind Farm.

Fjalla Power Station has been described earlier in this report, but it is not yet clear where the Wind Farm or Farms would be located. However, the current proposal that has been put forward is for Klausturselsheiði east of Jökla (Jökulsá á Dal).

Table 5. Financials of the 800 MW Fjalla Power Project and assocuated 854 MW Wind Farm

Interest rate	Percent …	6,00%			
ITEM	**UNIT**	**Hydro**	**Wind**	**Sum**	**Notes**
Unit Cost	MUSD/MW	2,5	1,171		Transmission included
Installed Capacity	MW	800	854	1.654	Total
Yearly production	GWh/year	4.000	3.000	7.000	Total
Utilisation	hours/year	5.000	3.513		
Yearly production	GWh/year	4.000	3.000	7.000	Total
Capital Costs, CC	MUSD	2.000	1.000	3.000	Total
Economic Lifetime	Years	60	25		
Annuity	Percent of CC	6,19%	7,82%		
Operation & Maint	Percent of CC	0,90%	1,50%		
Yearly Cost of Procuction	Percent of CC	7,09%	9,32%		
Yearly Cost of Procuction	MUSD/year	142	93	235	Total
Levelized Cost of Energy	**USD/MWh**	**35**	**31**	**34**	Weighted Average

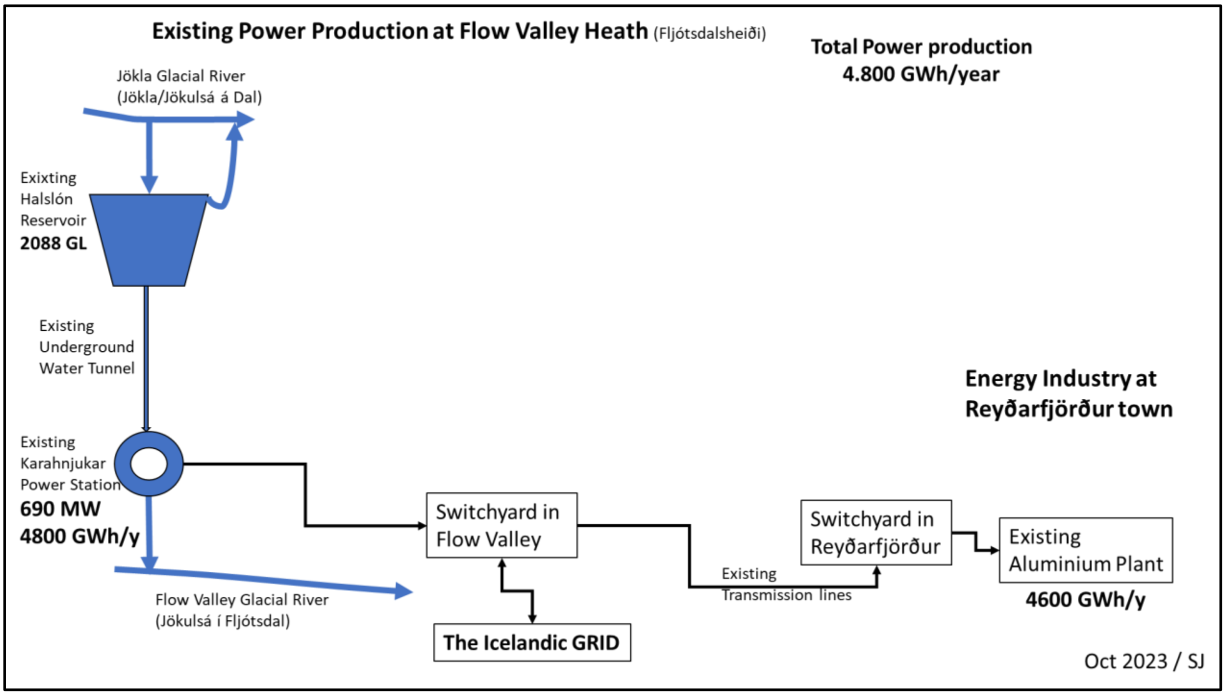
As mentioned earlier, the hydroelectric part, as represented by the Fjalla Power Station, will produce energy at a cost price of 35 USD/MWh, while the cost price of wind power is estimated to be 31 USD/MWh as demonstrated in table 5. The weighted average, with the weight of energy production, is then 34 USD/MWh, which must be considered extremely economical.

At this stage, it is difficult to give a more detailed account of the calculated costs, especially because the location and accuracy of the energy market have not yet been decided.

13. The overall picture then looks like this.

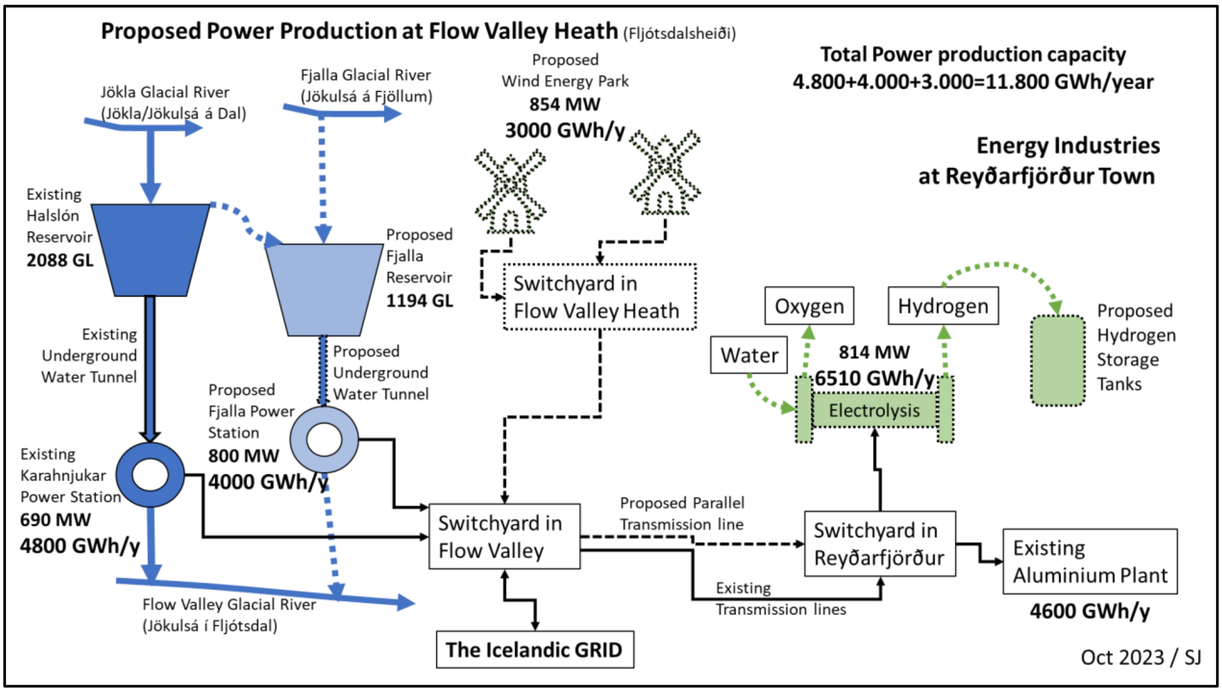
The existing electricity system for the large energy market in the East could look like shown in Figure 18. Total Power Production is 4.800 USD/year.

Figure 18. The current large energy market in East-Iceland



With our proposals for increasing the production of electricity using renewable energy sources, as presented by this report for power projects at the Flow Valley Heath, the focus now is how to utilize the harnessed energy in East-Iceland. The first thing that comes to mind is a hydrogen plant next to the Reyðarfjörður town near the site of the current Alcoa aluminum plant located there, see Figure 19.

Figure 19. Possible energy system expansion in East-Iceland



These power projects together with an idea for a hydrogen production at Reyðarfjörður are explained in Figure 19.

The hydrogen market needs to be defined in more detail and we are waiting for it until later.

With this implementation, the production capacity of the power plants at Flow Valley Heath increases by 7.000 GWh/year and will be a total of up to 4.800+4.000+3.000= 11.800 GWh/year, in an extremely economical way.

Assumed utilization of Power unit is explained in table 6.

Table 6. Assumed utilization of Power Units

Power Unit	**Installed Capacity**	**Production Capacity**	**Utilization**
	MW	GWh/year	hours/year
Kárahnjúkar Power Station	690	4.800	6.957
Fjalla Power Station	800	4.000	5.000
Wind Power Farms	854	3.000	3.513
Electrolysis	814	6.510	8.000

In Figure 19, an effort was made to have the existing structure with solid lines rather than the proposed structure with dotted lines and in a duller color, which hopefully succeeds as it should.

14. Potential electricity market

14.1 The Climate Situation in Iceland

At the outset, it is worth noting that the public in Iceland considers the situation in their climate matters to be quite good, as we have gone through the first two energy transitions with success and dignity, and which consist of:

1. The beginning of electrification in Iceland, that took place in Hafnarfjörður in 1904 with a 9-kW hydropower generator for a carpentry workshop. In 1937 the first public hydroelectric power plant with a capacity of 8,8 MW, Ljósafoss Power Station in the Sog river, was launched. A significant effort was made in the development of the Icelandic hydropower system with the commissioning of the 215 MW Búrfell power plant in the Thjorsa River in 1969.
2. Geothermal power plants for electricity production and direct use of geothermal for heating applications. The beginning of geothermal space heating in Iceland was back in 1909, but a lot of effort has been made in the development of house heating in Iceland sice the early 1970s, when the world market price of oil rose a lot. Before that time, Icelanders mostly used coal for space heating.

Coal for energy production was eliminated in the sixties and seventies of the last century, and Iceland is therefore one of the cleanest countries in the world. Older Icelanders remember well when the coal smoke in the capital gradually disappeared at this time, to everyone's delight. Unfortunately, sometimes it is seen otherwise, even by environmentalists and committees in the public sector, but their issues have infrequently been put in extreme forms in support of their cause and one should be careful not to take too much notice of that. The situation is often described as dire in the news, which in most cases is attributed to information from public sources, mainly the government.

On May 17, 2022, we sent a letter to the Icelandic Ministry of the Environment, Energy and Climate, due to the Climate Action Plan June 2020, claiming that:

> *With the Paris Agreement of 2015, we in Iceland must reduce the emission of greenhouse gases in cooperation with other nations so that the rise in temperature caused by this remains in 2050 less than 2°C and ideally does not exceed 1,5°C from the situation before the industrial revolution, say from the year 1850. Now that year has long passed, but the question is which starting year should be used when evaluating climate action?*
>
> *European nations have used the year 2005, as nothing was done there in terms of climate before that time.*
>
> *Icelanders had long since begun to use renewable energy, hydropower, and geothermal energy to generate electricity and, in addition, large-scale heating projects that eliminated coal for domestic heating in the second half of the twentieth century.*
>
> *Therefore, it is reasonable to assume that the starting year in the assessment will be no later than some year between 1930-60 and that full consideration should be given to Icelanders' actions in activating renewable energy before 2005.*

A reply to this query has not yet been received.

14.2 Electrolysis and ammonium plant at Reyðarfjörður. A centralized solution.

In figure 20 and table 7 you the installation in East Iceland is explained, where the Fjalla Power Project and the associated wind farm are located on the Flow Valley Heath. Also, the expansion of the energy market in Reyðarfjörður Town located in East Iceland with a large electrolysis equipment to produce hydrogen and a factory for the continued production of ammonia from hydrogen and nitrogen, that would be extracted directly from air at the place.

Figure 20. Schematics over the new power plants at Flow Valley Heath and the associated expansion of the energy market at Reyðarfjörður.

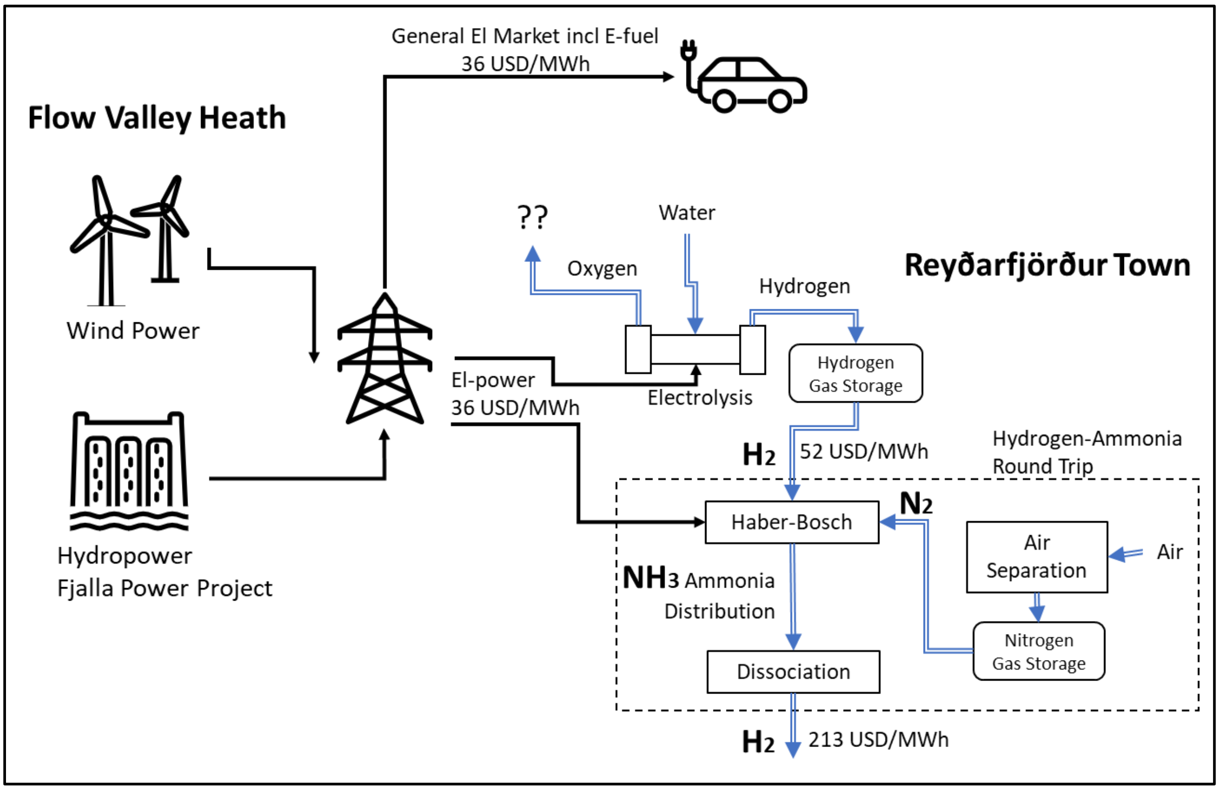


Table 7. Characteristics of Fjallapower with Hydrogen and Ammonium Production

Assumptions								
Interest rate	6%							
Power	Capital Costs	Installed Capacity	Power Production	Utilization hours	Cost of Operation	Energy Losses	Lev.Cost of Energy	Cumulated Costs
Delivered at Reyðarfjörður	MUSD	MW	GWh/y	h/year	MUSD/y		USD/MWh	USD/MWh
Fjalla Power Project	2.000	800	4.000	5.000	142		35,44	
Fjalla Wind Farm	1.000	854	3.000	3.513	93		31,08	
Total	**3.000**	**1.654**	**7.000**	**4.232**	**235**	7%	36,09	36,09
Hydrogen-Ammonia								
Electrolyzer	674	814	6.510	8.000	83	20%	15,95	52,04
Ammonia Round Trip	1.900	651	5.208	8.000	234	72%	160,56	212,60
Total	**2.574**		**1.458**		**317**			
References								
https://www.sciencedirect.com/science/article/pii/S0016236123024572								

With this, the annual production capacity would be 130.200 tons of hydrogen, resulting in an annual production of ammonia of 720.233 tons.

Thereby, the cost of producing hydrogen is estimated:

52,04 USD/MWh * 7.000.000 MWh/year / 130.200.000 kg-H_2-year = 2,80 USD/kg-H_2.

Oxygen produced during electrolysis could even be sold. In the scientific articles we have reviewed, it is usually assumed to release the oxygen into the atmosphere, but it may be that in Iceland a market for pure oxygen is opening in fish farming on land. The sale of oxygen could then lead to a reduction in the cost price of hydrogen. We have investigated this further, without reaching a conclusion, but are still considering the matter.

In the column 'Cost of Operation' we have estimated that for Fjalla Power Project (lifetime and fixed operating costs) = (80 years; 0,9% of initial cost), for wind farms (25 years; 2,5%) and for factories (25 years; 4,5%). This information is not visible in the table but is hardwired into the formulas behind the values. It was done to not overload the table too much.

The production cost of electricity from the Fjalla Power Project in cooperation with the Wind Farm and with delivery to Reyðarfjörður will be **36 USD/MWh,** which is considered very cost effective.

If the electricity is used to produce green hydrogen by electrolysis at Reyðarfjörður, it is estimated that the energy price will increase by 16 USD/MWh and the energy cost of hydrogen from the electrolysis will then reach **52 USD/MWh**.

Presumably, there will not be a market for all this electricity in Reyðarfjörður, and it would then have to be transported by some means to other places. A reasonable option for this is to combine hydrogen and nitrogen, which would be extracted from the atmosphere at Reyðarfjörður in a factory. The production cost of ammonia and conversion back to hydrogen at place of delivery (the Round Trip Cost) would be 161 USD/MWh. Ammonia could then be transported to nearby places, e.g., elsewhere in Iceland or to distant places, e.g., abroad, probably to Europe. The cost of transportation, which in most cases would be seaborne, has not yet been included in the energy price of 213 USD/MWh.

The summary and conclusion here is that:

1. With the 800 MW Fjalla Power Project and the associated 854 MW Wind Farm, it will be possible to produce electric power in a very economical way. At the same time, it would be most efficient to use the electricity directly to meet the growing electricity consumption by existing and new electricity buyers in Iceland, including for electric vehicles.
2. The production of green synthetic fuel is inefficient, and it is necessary to look for ways to avoid it. The production and transport of this fuel refers to the fact that most of the electricity produced by harnessing natural and renewable energy sources, will go straight into the air as energy losses.
3. In that respect it is most important to consider that at atmospheric pressure ammonia liquefies at -33 degrees Celsius but hydrogen at -253 degrees Celsius, and hydrogen is therefore many times more difficult to handle than ammonia.

14.3 Transportation of green fuel

Our literature review has revealed that the storage and distribution of hydrogen over long distances either with or without the use of ammonia as an intermediate, has a similar overall cost.

The results of the last subchapter led to the fact that the idea of producing synthetic fuel from green hydrogen in Iceland is bad, as it seems to be extremely inefficient for domestic use.

It is surprising that all the domestic energy companies, institutions, and organizations that have discussed this issue in recent years, including creating high-flying electricity forecasts, did not comment at all on this side of the matter.

Considering this, the Icelandic legislator's decision to move the ban of fossil fuels from 2050 forward to 2040 is incomprehensible. It would only lead to a widespread and unacceptable payment problem in society.

There must be other ways to deal with the climate problem using more cost-effective solutions in the situation.

Despite this, the Icelandic electricity market is forecasted to become large enough in the coming decades to be able to accept a large hydropower plant such as the Fjalla Power Project with the planned associated Wind Farms. According to what has been stated above, the overall conclusion is that such valuable electrical power should not be wasted on power to produce gas or liquid made synthetic e-fuel.

14.4 Another proposal for a distributed solution.

The obvious solution in the situation here is that, instead of distributing the green energy, from Fjalla Power Project and the associated Wind Farms, around the country with synthetic fuel such as ammonia or methanol, it should rather be done by electricity in the traditional way with high-voltage transmission lines.

As part of such a solution, the transmission line between East Iceland and the Thjorsa region, where most of Landsvirkjun’s hydropower stations are located, would be reinforced with a high-voltage transmission line. Either take the highland route north of the glacier Vatnajökull or the land route south of glacier.

The length of these routes is each 150-200 km and should therefore cost approximately 170 km * 3 MUSD/km ≈ 500 MUSD whichever route is chosen. These cost figures are for information only, but let's take a closer look at the current transport tariff in Iceland.

The transmission fee for high-voltage transmission at the Icelandic Power Company Landsnet is 1,5 USD/MWh. Added to that is a power fee, which is loosely estimated here at 33% or 0,5 USD/MWh. The transfer fee is then estimated at 2 USD/MWh. In doing so, the electrical power cost would increase from 36 USD/MWh to 38 USD/MWh and 16 USD/MWh for the electrolysis results in production cost of **54 USD/MWh**. That is only a fraction of what it costs to produce ammonia and later convert it back into hydrogen at the point of delivery, as estimated in the last subchapter to be 213 USD/MWh.

With the suggested solution for the production and distribution of hydrogen, fuel stations would be created throughout the country where the following operations would be carried out:

1. Charging Station for electric cars.
2. Hydrogen production, incl. electrolysis and hydrogen storage tank, and sales. (Ref: YouTube video: “On-Site Hydrogen Production Refueling Station (FPM-02), University of Guelph W21 Engineering & Design 3”)
3. Sales of traditional fossil fuel Diesel and Gasoline.
4. Point of sale for consumer goods.
5. Etc.

This of course means that there would be many such distribution centers located in the Reykjavík Capital Area but also one by one all over the rural Iceland.

This is a proposal that is similar to the traditional gas station that has been part of the streetscape of Icelanders in recent decades. A station with both the old arrangement for the sale of petrol and diesel and the new one where there is a direct delivery of electricity and hydrogen produced from electricity on site. According to the intention of the law, the volume of sales of oil fuel should gradually disappear. The competition would be forced by the intention and measures of the legislature, such as taxation.

A more detailed discussion of the organization of vehicles fuel sales centers is outside the scope of this review.

15. Potential Investors

The following three parties, along with their business partners, have shown interest in the project.

This is an extremely large and costly project, and it is not certain that the financial capacity is available within the country to bring it to fruition. It does, however, lead to major benefits in terms of a reduced carbon footprint and lower penalty fees if national targets are not met. This project is therefore an interesting alternative in the situation that the government of Iceland has already determined by law to be in 2040.

If there was interest in the participation of domestic parties in financing, it would certainly be welcomed.

Richard Friedman, USA

Richard L. Friedman is a real estate developer involved in multiple business, civic, and charitable endeavors.[1] Friedman is the President and CEO of Carpenter & Company, Inc. of Cambridge, Massachusetts, a private firm involved in real estate and private investments. Carpenter specializes in hotel development.

Richard is the prime owner/developer of Edition Hotel Reykjavik and partner of Bill Gates.

Robert McEwen, Canada

Robert is the chairman and chief executive officer of McEwen Mining.

Robert is releasing 750 m$ to charity and environmental projects.

Evan Goldman

Evan Goldman was instrumental in financing Bright Source Energy in the US. A 3 billion $ solar project.

16. Dettifoss Waterfall and Einar Benediktsson

Here is the first verse of the famous poem Dettifoss by Einar Benediktsson (1864-1940), composed 1905 and published in the Einar Ben's poetry book Hafblik 1906.

In Icelandic

Syng, Dettifoss. Syng hátt mót himins sól.
Skín, hátign ljóss, á skuggans veldisstól.
Og ký minn huga, gnýr, til ljóða, er lifa,
um leik þess mesta krafts, er fold vor ól.
Lát snerta andann djúpt þinn mikla mátt,
sem megnar klettinn hels af ró að bifa.
Ég veit, ég finn við óms þíns undraslátt
má efla mannleg hjörtu. Slá þú hátt,
fosshjarta. Styrk minn hug og hönd að skrifa.

… and in English with straightforward computer translation

Sing, Dettifoss. Sing high against the sky's sun.
Shine, majesty of light, on the throne of shadow.
And drive my mind, rumbles, to poems that live,
on the game of the greatest power, is the fold of our strap.
Let your mighty power deeply touch your soul,
which allows the rock to rest in peace.
I know, I feel a sense of wonder at your resonance,
human hearts can be strengthened. Hit you loud,
waterfall heart. Strengthen my mind and hand to write.

In the summer of 1904, Einar Benediktsson and his wife Valgerður Zoéga travel around the North of Iceland.

They come to Dettifoss, where the great waterfall is struggling, to no one's benefit. In the poem, Einar has the power of the waterfall in a higher position and made it a kind of symbol of the comprehensive restoration of the country and the nation.

Einar connects the power plant of Dettifoss with a fertilizer factory: "And the fertile air can be drawn to flowers and birch / yes, the clothing of the heat is made from the clothes of a glacier". It was this dream vision that fascinated the mind the most. In it, the poet and the realist were united. The beauty of the waterfall blew the poet's mind away, but the giant mother made the realist think that here was the grotto mill that could grind gold and prosperity for the nation, if it was right.

A fertilizer factory is going to be the focal point of Einar Benediktsson's ideas about the activation of waterfalls and heavy industry in Iceland.

The Icelandic composer Jón Leifs created his tone paintings of Icelandic natural wonders, including Dettifoss (1964). Here he conceived a dialogue between poet Einar Benediktsson and the huge waterfall rather than a straight depiction. Thumpingly good performances from all concerned, captured in spectacular sound to match the landscape.

End of Report