Technical University of Denmark

Energy System Analysis for Iceland using the concept of Energy Scenarios

Implementing Iceland into the energy model BALMOREL

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Abstract

In Iceland, the energy system is characterized by a high utilization of local renewable resources. Both hydro- and geothermal resources are abundant in Iceland and these two resources supply most of the energy demand in Iceland. In the year 2010, hydro power plants produced around 74% of the total electricity generation and the remaining 26% were produced by geothermal power plants. District heat is produced by using geothermal heat and is mainly used for space heating in the residential sector. A great majority of the electricity generation in Iceland is consumed by energy intensive industries or more than 80%. In this study, the Icelandic energy system is described and its development until the year 2050 is analysed by using the concept of energy scenarios. This type of analysis is not widespread in Iceland and is evaluated as a useful tool for analysing the development of the Icelandic energy system. Three energy scenarios were created in this study and are based on some of the future options that Iceland is facing. Of these options, the export electricity through a submerged transmission cable to Europe is being discussed and the project is now considered both technically and economically feasible. Another option is the continuing penetration of energy intensive industries in the energy system in Iceland. Both of these options are energy intensive and could have large impacts on the energy system and the resources in Iceland. Excessive production from the hydro and geothermal can have negative impacts on the environment and the society and a master plan for the hydro- and geothermal resources has been developed in Iceland to minimize those impacts and to rank proposed power plant options based on economic, environmental and social factors. In the work presented here, the Icelandic energy system is implemented in the energy model BALMOREL and the energy scenarios created are simulated and analysed. The results from the simulations suggest that investment in new power capacity is needed to meet the increased demand for electricity and that the electricity production from hydro and geothermal resources might be exceeded in the next decades, requiring that other sources of energy are exploited.

Preface

This report was written for a 30 ECTS point master project at the department of Sustainable Energy, Technical University of Denmark (DTU). The work was performed at the department of DTU Management Engineering in the year 2012.

I would like to express my gratitude to my supervisors, Kenneth Karlsson and Marie Münster for their guidance and support through the work of this project. Special thanks I would like to give to Olexandr Balyk for his immense patience and interest in helping me understanding the BALMOREL model and to Hans Ravn for giving me very helpful advices and comments. I would also like to thank Jónas Hallgrímsson from the University of Iceland for a good cooperation in the beginning of my project. And of course I would like to thank my family and my girlfriend Evita for all the kindness and support they have given me in the past months.

Table of Contents

1. Introduction

The world currently consumes large amounts of fossil fuels which release unwanted CO_2 to the atmosphere, inducing the effect of global warming. These fossil fuels have been created through millions of years and the reserves are diminishing with the current pace of extraction. Many countries do not have large fossil fuel resources and have to depend on imports from other countries. Fossil fuel is the most important source for energy in most countries and are used e.g. for transportation power production and space heating. A shortage of fossil fuels can therefore be catastrophic and becoming less dependent on fossil fuels should therefore be an obvious choice for each country. This is a challenging task and requires a paradigm shift on behalf of the authorities and the societies.

The list of alternative sources of energy to fossil fuels is long and the technologies those sources are developing fast, becoming more efficient and cheaper as the experience of using them grows. Among the developed technologies are onshore wind power, near coast offshore wind, hydro power and geothermal power. Other technologies such as deep sea offshore wind power and ocean power are gaining momentum but the costs are yet considerably higher than for developed technologies. This is likely to change in near future with the implementation of new offshore wind-farms and by a growing expertise in these fields.

In this project, focus will be on the energy system in Iceland which currently produces almost all of its electricity by use of renewable energy. Iceland utilizes its mountainous landscape and geographical location to produce electricity from water and geothermal heat. These two technologies have served the electricity demand in Iceland from 1904 when electricity was first established [1]. Hydro power was utilized first, and in 1969 the first geothermal power plant was commissioned [2]. Geothermal heat is furthermore utilized for district heating and supplies the capital city with most of its heating demand. The two technologies are well established and expertise is high. Especially in the utilization of geothermal energy, Iceland has earned a good reputation and is currently hosting a post-graduate geothermal training programme of the United Nations University which has the aim to support developing countries in exploitation and development of geothermal energy [3].

Iceland currently has abundance of energy resources to supply its own demands for heat and electricity. Energy for transportation is however entirely dependent on oil imports. The large amount of geothermal heat and hydro power available in Iceland is drawing attention by other countries and discussion on exporting electricity through a transmission cable to Europe is getting louder. This increased interest is due to the low cost for energy production in Iceland compared to Europe where the prices are constantly rising. Installing the transmission cable is now considered both technically and economically feasible and the energy ministries of Iceland and the United Kingdom (UK) have recently shown the project interest. Likewise the national power company has published their interest in the project [15].

With increased demands for electricity and heat within all sectors of the society in Iceland, the future is hard to predict. Recent political decisions have furthermore introduced energy demand from energy intensive industries that have led to noticeable changes in the energy demand for the entire country. These political decisions make future predictions for energy demand even less reliable requiring other types of methods to be used. In this thesis, the concept of *energy scenarios* is introduced as a means of analysing the development in Iceland in the next few decades. This type of analysis is not commonly used in Iceland and no previous work on this matter was found to have been laid out. Energy scenarios can give a good idea of possible futures for the Icelandic energy system and the work presented here can thus be considered as preliminary attempt to such analysis.

In order to facilitate the use of energy scenarios as an analysis tool, an overview of the Icelandic energy system is necessary. For this purpose an energy analysis tool (energy model) named STREAM is used for collecting some of the basic data needed for building up the energy system in Iceland. Once an overview of the Icelandic energy system has been attained, the possible future development of the system is discussed based on historical development and on governmental policies and plans. From this discussion on the future development of the Icelandic energy system, a few energy scenarios are created for Iceland and are implemented in another energy model, BALMOREL, and simulated. This model optimizes the operation of the Icelandic energy system and seeks to minimize the operating costs of the whole system for each year in the simulation. It can prove useful for a large variety of applications and by implementing Iceland into the BALMOREL model; the basis for such applications can be established.

The motivation for this study is to cast a light on the development of the Icelandic energy system; both at present and in the coming decades. Increasing demand for electricity from energy intensive industries and from a transmission cable to Europe could have large effects on the Icelandic energy system and its energy resources. The energy resources of hydro and geothermal heat are large in Iceland but excessive use of these resources can have negative impacts on both the society and the environment. It is therefore essential that these resources are used properly and a long term management of these resources is already being discussed in Iceland. The use of energy scenarios and energy analysis tools such as STREAM or BALMOREL, the response of the Icelandic energy system to the increased demand from energy intensive industries and from the (possible) transmission cable to Europe can be analysed thoroughly. The use of energy scenarios and energy analysis tools can furthermore ensure that informed decisions are being made to the benefit of the society in a long-term perspective.

2. The Energy System in Iceland

Iceland is an island in the North-Atlantic Ocean with a population of around 330.000 and with an area of around 103.000 km^2. This gives a population density of around 3 persons per km^2, which is the lowest population density in Europe [6]. Most of this area is undertaken by volcanic deserts and glaciers and is therefore not inhabitable. Iceland is located on the Mid-Atlantic Ridge, which marks the boundary between the Eurasian and the North-American tectonic plates [19]. Volcanic activity is high and great amount of geothermal heat is more easily accessible than in other countries around the world. The utilization of geothermal heat has grown in the past few decades and geothermal heat is now the main source of energy for heating purposes in Iceland. In addition to the geothermal heat readily available in Iceland, the mountainous landscape is subject to a high level of precipitation and immense amounts of water flows in rivers from the highlands and down into the sea. Many of those rivers are glacial and the flow is therefore closely related to the melting of the glaciers. This is mostly a seasonal variation but increased flow in the rivers has recently also been linked with global warming. The energy resources of geothermal heat and water are harnessed for electricity and heat production and currently deliver most of the total energy demand in Iceland. With the abundance of both water and geothermal heat in Iceland, the exploitation of other resources for power and heat production is minimal. Imports of oil are necessary for transportation, aviation and the fishing fleet and small amounts of coal are imported for industrial processes. The energy demand is otherwise met by renewable energy resources of water and geothermal heat which are found locally.

In this section, an overview of the Icelandic energy system will be given. The total fuel consumption in Iceland and the consumption in different sectors of the society are discussed in section 2.1. The demand and the production for heat and electricity are then discussed in sections 2.2 and 2.3 respectively and the electricity network in Iceland is discussed in section 2.4.

2.1. Fuel Consumption and its Utilization

The historical development of the *primary energy consumption* in Iceland can be seen in Figure 1 below. It shows that the consumption has increased significantly in the past few decades and the total consumption was 234.1PJ in the year 2010 [8]. This is a consumption of around 750GJ per capita which is very much compared to the consumption in other countries. The reason for this high consumption can be explained partly by a high penetration of energy intensive industries in the Icelandic energy system compared to the population of Iceland. It can also be explained by the fact that geothermal heat is used for power production with large amounts of waste heat. The cold climate in Iceland furthermore increases the need for space heating compared to countries in a warmer climate.

The *increase* in the energy consumption shown in Figure 1 for the last decades can partly be explained by the transition of space heating from the use of domestic oil-fired boilers to the use of a district heating which utilizes geothermal heat. The utilization of geothermal heat for power production has in addition been recently introduced in Iceland. For the year 2010, the primary energy consumption of geothermal heat was 155.2PJ[1], which corresponds to 65.7% of the total primary energy consumption

[1] The primary energy consumption for geothermal heat is calculated as the energy released as it cools down to a temperature of 15°C (and releases its pressure down to 1 bar) [9]

for that year [8]. The contribution of other forms of primary energy for the year 2010 can be seen in Figure 2. Consumption of water for energy production is 19.2% of total primary energy consumption[2], oil consumption is 13.5% and consumption of coal is 1.6%.

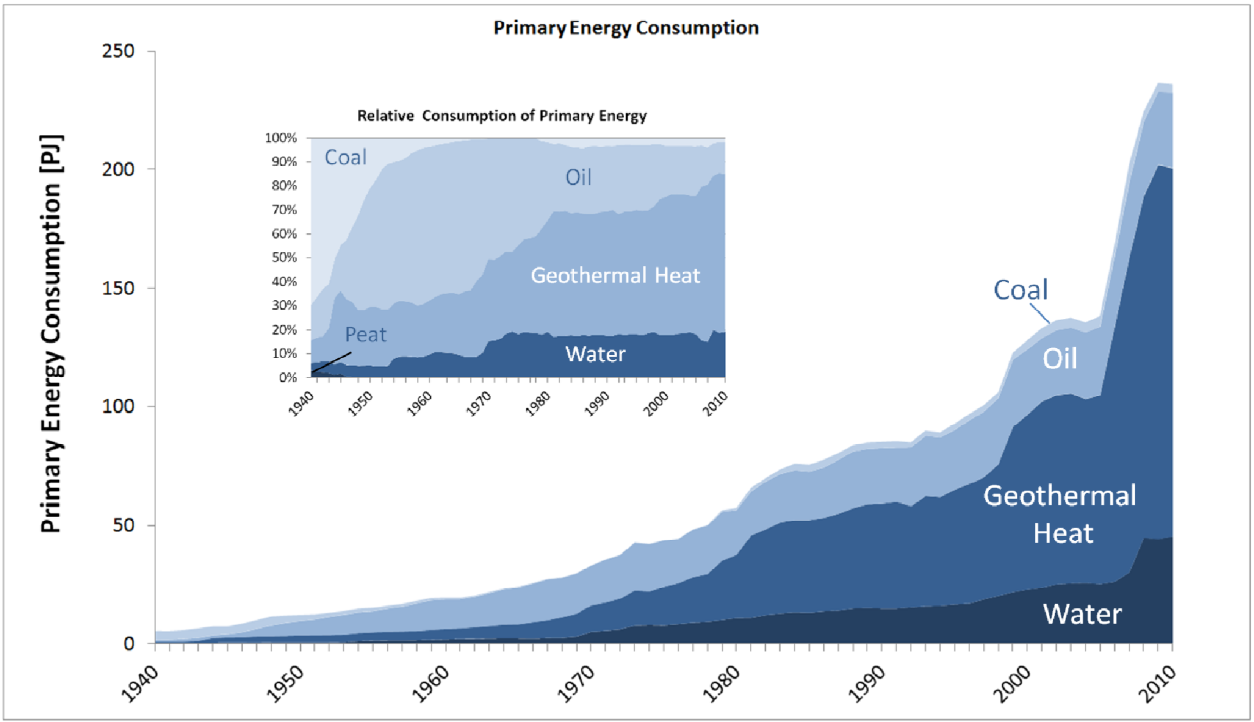


Figure 1: The Primary energy consumption in Iceland from the year 1940 to the year 2010 [8]

[2] The primary energy consumption of water is assumed the same as the electricity generation from hydro-power plants [9]

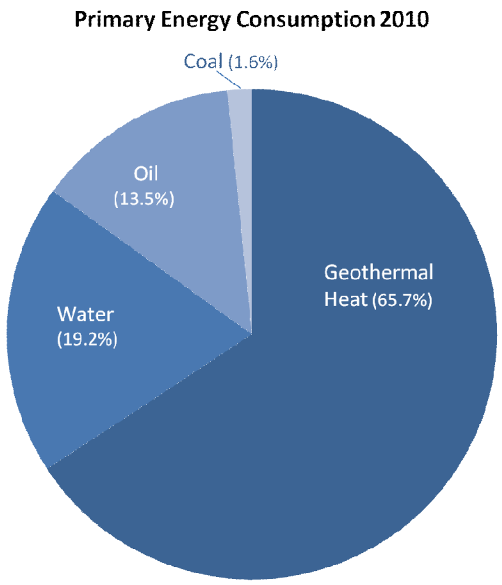


Figure 2: Share of primary energy consumption in Iceland for the year 2010

The primary energy consumption shown in Figure 2 is the consumption of primary energy resources such as water, oil, coal and geothermal heat. These are the fundamental energy resources that the energy system in Iceland is built upon. These resources are either used directly or they are converted to another form of energy. This is done with the use of *energy conversion technologies* which convert the energy to a more useful form such as electricity or heat. In Iceland, heat is delivered to different sectors of the society through district heating networks. This district heating is in Iceland fuelled entirely by geothermal heat. Consumers in different sectors of the society can utilize this district heat and it can therefore be considered as a fuel in a similar way to the water is a fuel for the hydro power plants. Same applies to the electricity which is used as a fuel for various electrical devices and appliances in different sectors of the society. The total *fuel consumption* for Iceland in the year 2010 can be seen in table 2-1 and is also shown in Figure 3 for clarity. It can be seen that most is consumed of geothermal heat or in total 155.2PJ. This is around 50% of the total fuel consumption and shows the importance of geothermal heat in the Icelandic energy system. The reason for this high consumption is the large amounts of heat needed in geothermal power plants to produce electricity, i.e. the low fuel efficiencies of the geothermal power plants and large amounts of waste heat.

2-1: Total fuel consumption in Iceland for the year 2010

Fuel consumption 2010	Total fuel consumption *(PJ)*	Reference
Geothermal heat	155.2	[8]
Water	45.3	[8]
Oil	29.6	[8]
Coal	4.0	[8]

Electricity[3]	59.7	[12]
District heating[4]	25.3	[57]

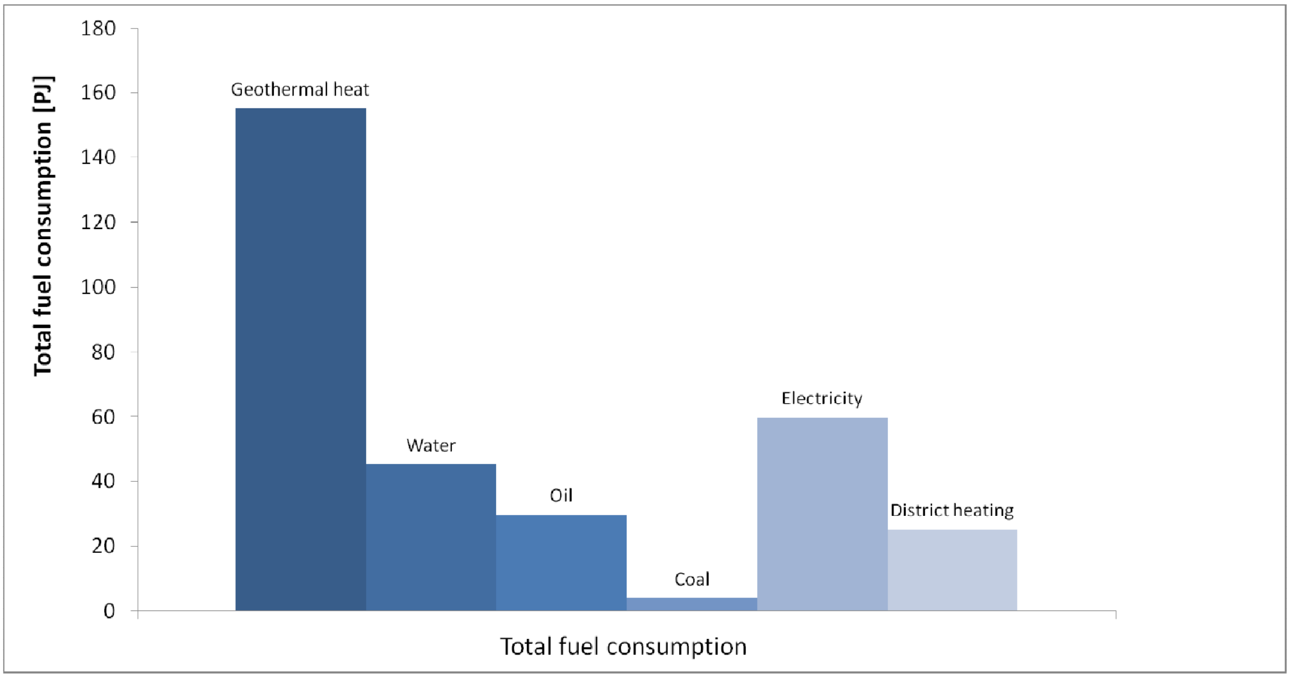


Figure 3: Total fuel consumption in Iceland for the year 2010 (adopted from [8], [57] and [12])

In order to produce electricity and district heating, primary energy is consumed and the contribution of the primary fuels to the electricity and district heating production is shown in Figure 4. It shows that the power production in Iceland consumes only geothermal heat and water. Since geothermal heat and water is considered to be renewable energy resources, the power production in Iceland is unique compared to other counties around the world where the power production is often based on a high share of fossil fuels. The district heating production consumes only geothermal heat.

[3] Electricity consumption is calculated from [12] and the distribution losses of electricity have been excluded.

[4] Assuming that heat is supplied through district heating networks for all consumers. Data is only available for the year 2009 and it is assumed that the district heating consumption is the same as in 2010. Only geothermal heat is assumed to be used for district heating.

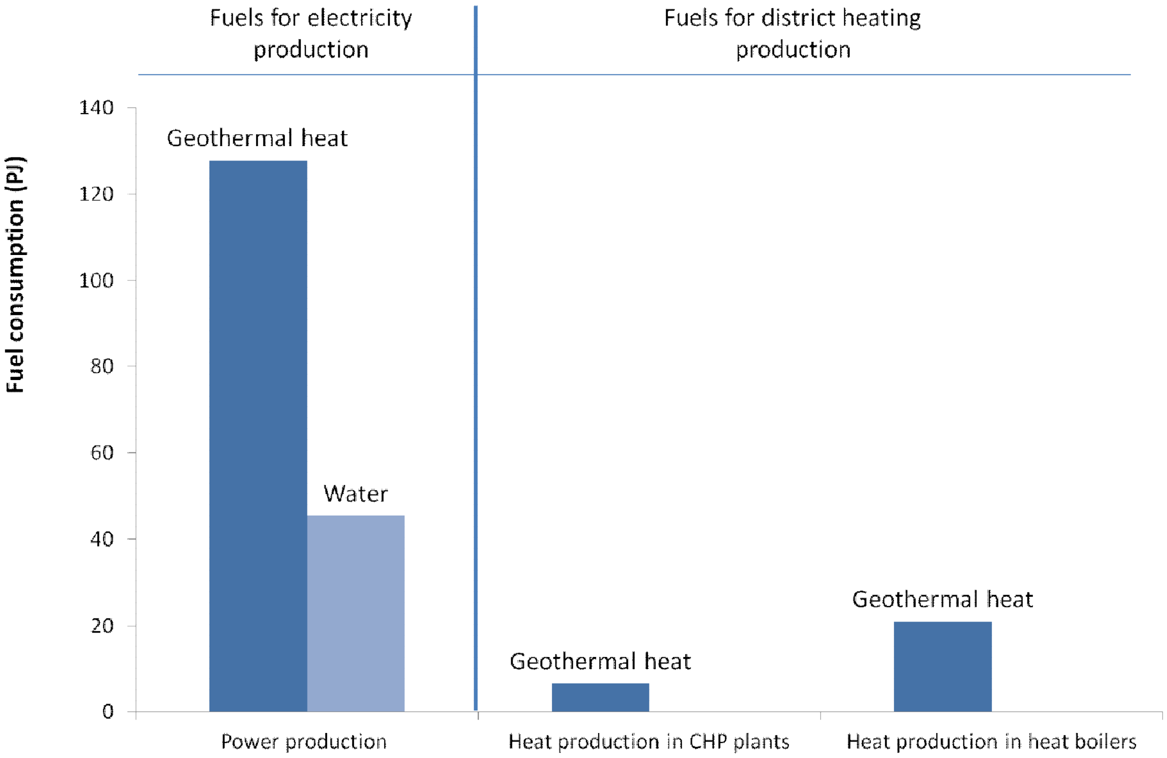


Figure 4: Primary fuel consumption for power and heat production. Fuel consumption for power and heat production in geothermal CHP plants is allocated based on a fuel efficiency of 200% for the heat output.

The total *fuel consumption in different sectors* of the society is shown in Figure 5 below. Power production sector is the highest consumer of fuel and the fuel consumption is more than 50% of the total consumption from all sectors. This is under the assumption that for geothermal units that produce power and heat (CHP units), the production of power is allocated most of the fuel consumption. It is assumed that 95% of the geothermal heat used as fuel in CHP units is allocated to the electricity production while the remaining 5% of the geothermal heat is allocated to the heat production. The allocation method involves the assumption of fuel efficiency for the output heat of 200% and is a method that can be used for this purpose[5]. This means that electricity is considered the primary product of the geothermal power plants and the heat is considered a secondary product. This is however a subject of discussion and other allocation methods could have been used for this purpose. An example of other methods is the allocation of fuels based on costs and allocation of fuels based on energy content[6].

The industrial sector is the second largest consumer of fuel and other sectors use significantly less. It can therefore be concluded from preceding discussion that the power sector and the industrial sector in Iceland are the sectors of most importance in terms of total fuel consumption.

[5] This means that for a CHP plant with a fuel consumption of 1PJ and a delivered energy output of 0.5PJ of heat and 0.5PJ of electricity, the heat output is allocated 0.5/2 = 0.25PJ of the fuel consumption for the CHP plant while the electricity is allocated the remaining fuel consumption of (1-0.25)=0.75 PJ.

[6] These methods are e.g. used in the study-field of Life Cycle Analysis (LCA) for determining the environmental impacts from various processes and will not be discussed here.

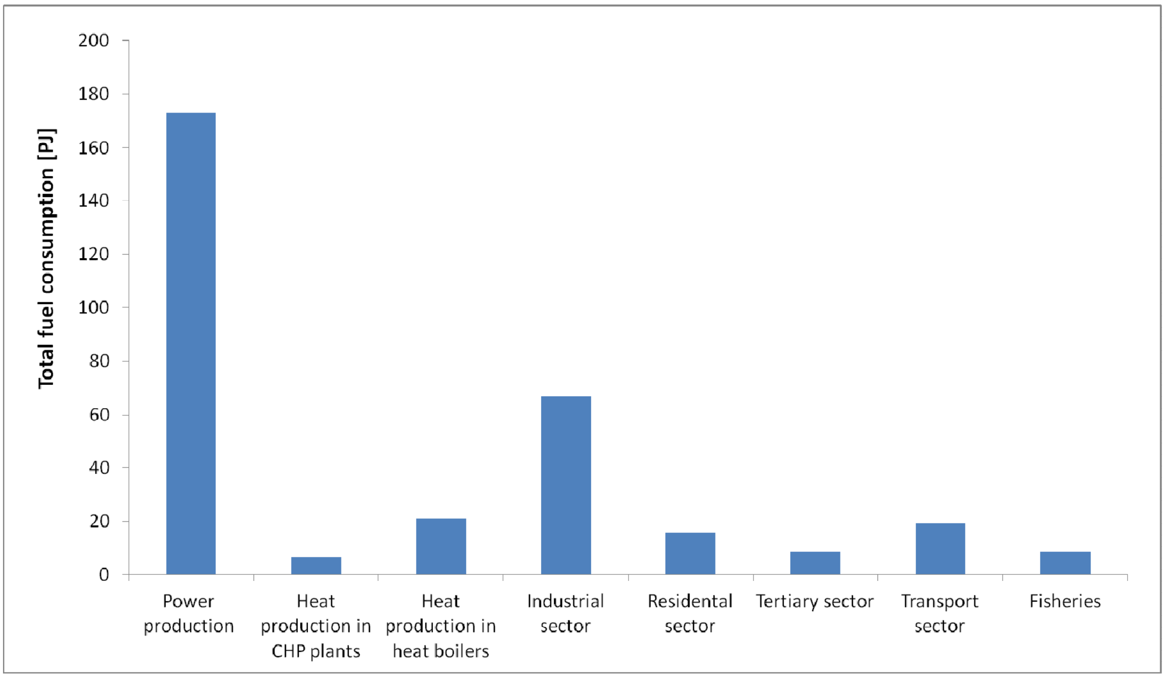


Figure 5: Total fuel consumption in different sectors in Iceland for the year 2010

The *type of fuels used in different sectors* of the society for the year 2010 can be seen in Figure 6 below. The consumption quantity of each type of fuel is also shown. For the quantity to be shown, aggregation of data into relevant sectors of the society was needed (see aggregation procedure in the appendix). The Aggregation is based on data found in [12], [57] and [58] and was necessary due to the fact that data in Iceland is primarily collected on the consumption side and is not divided on different sectors of the society.

The consumption of electricity in the industrial sector is the most important category with a consumption of more than 50 PJ (13.8 TWh). Other fuels used in the industrial sector are used in significantly less amounts. The residential sector consumes the highest amount of district heating among the sectors or around 10 PJ (2.7 TWh). The consumption of other fuels than district heating in the residential sector is lower than 5 PJ (1.4 TWh). The tertiary industry consumes district heating and electricity somewhat to the same level or around 5PJ (1.4 TWh). The transportation sector is mainly fuelled by oil and the consumption is around 20PJ (5.6 TWh)[7]. The fishing fleet consumes around 10 PJ (2.7 TWh) of oil. The oil consumption in sectors other than the transportation sector and for the fisheries is less than 2 PJ (0.5 TWh).

[7] The consumption of oil covers both the use of diesel oil and gasoline in all vehicles in Iceland. The amount of vehicles that utilize other fuels than gasoline and diesel is less than 10% of the total registered vehicles in Iceland [59] and the energy consumed by these vehicles is here omitted due to the lack of data available on the matter.

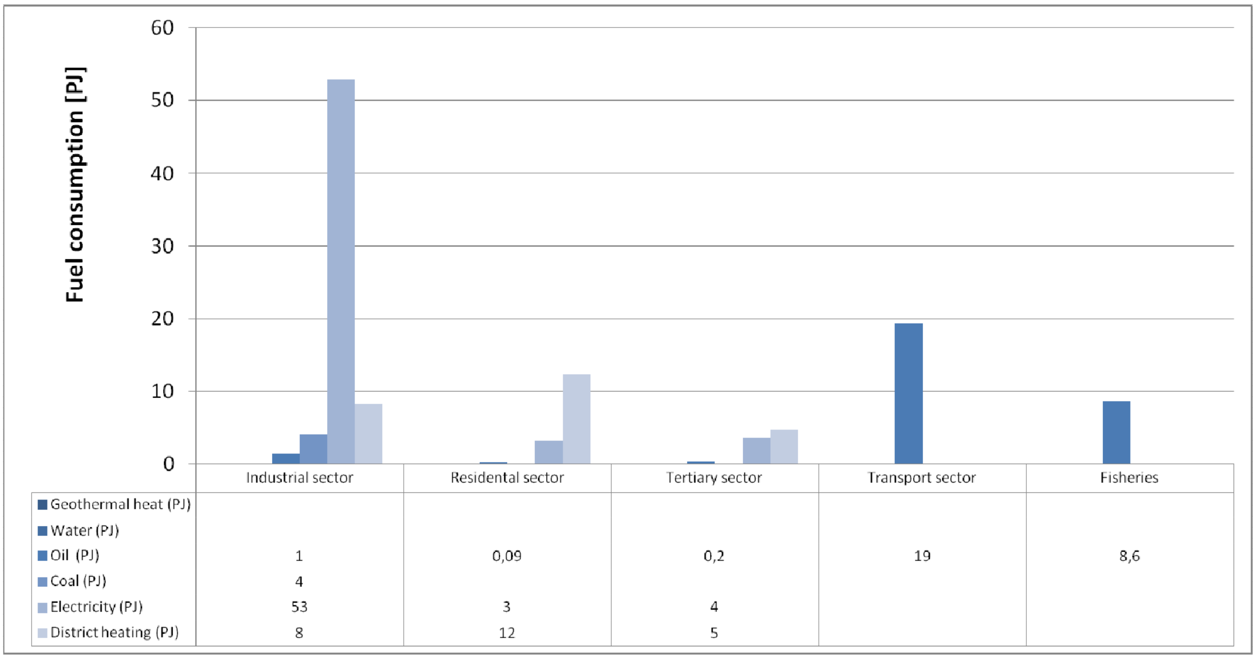


Figure 6: Fuel consumption in different sectors of the society for the year 2010 (assumptions on the aggregation are found in the appendix)

2.2. Heat Demand and Production

The total *demand for district heat* is shown in table 2-2 below and the contribution of each sector to the total demand for heat and is shown in Figure 7. In total a heat consumption of 25.3 PJ was consumed of district heating in the year 2009 [57]. Residential sector consumes around half of the district heating demand and the industrial sector consumes slightly more than the tertiary sector. As can be seen in Figure 4, the production of district heat in Iceland uses solely geothermal heat as a fuel. Geothermal heat is abundant in Iceland and the heat is used for various other purposes than for space heating. This includes the use of geothermal heat for the heating of swimming pools, snow-melting systems, fish farming, greenhouses and various industrial processes. The district heating therefore supplies all these consumers with heat and the share of consumption of these consumers is shown in Figure 8. Not all households can though be supplied with district heat in Iceland. These households are too remote to connect to the nearest district heating network and supply their space heating demand by use of domestic oil-boilers or electric heaters. The share of fuels used for space heating is also shown in Figure 8. In total around 89% of the space heating is provided by use of geothermal heat, 10% of the space heating is provided by oil and 1% is provided by electricity [60].

2-2: Consumption of district heat within different sectors of the society for the year 2009.

Demand for district heat	District heating *(PJ)*
Industrial sector	8.3
Residential sector	12.3
Tertiary sector	5.3
Total demand for district heat	**25.3**

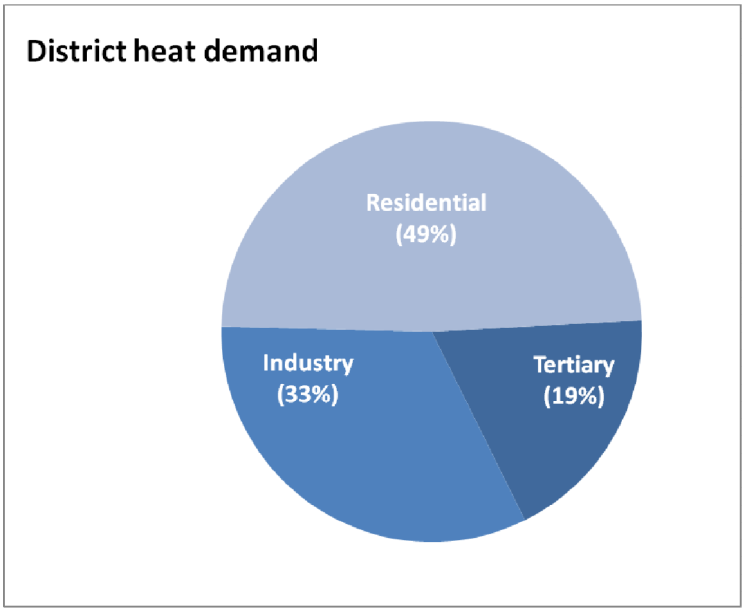


Figure 7: The share of industry, residential- and tertiary sector of the district heating demand for the year 2009.

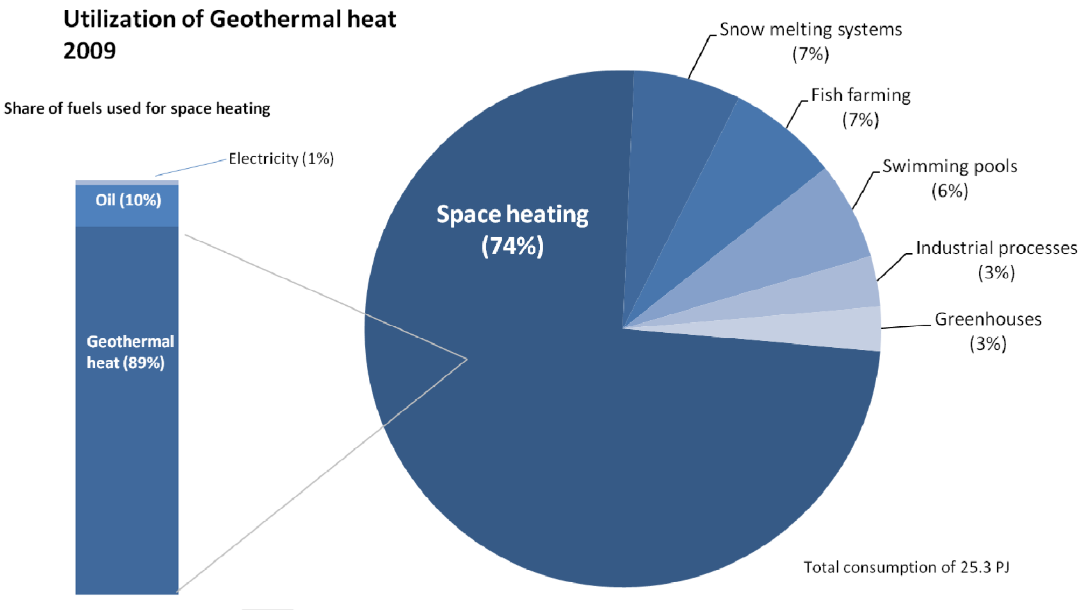


Figure 8: Direct utilization of geothermal based district heat in Iceland for the year 2009 [57]. Utilization of geothermal heat for power production is excluded. The share of fuels used for space heating is also shown. The space heating shown covers 89% of the total space heating demand, the rest being supplied by oil and electricity.

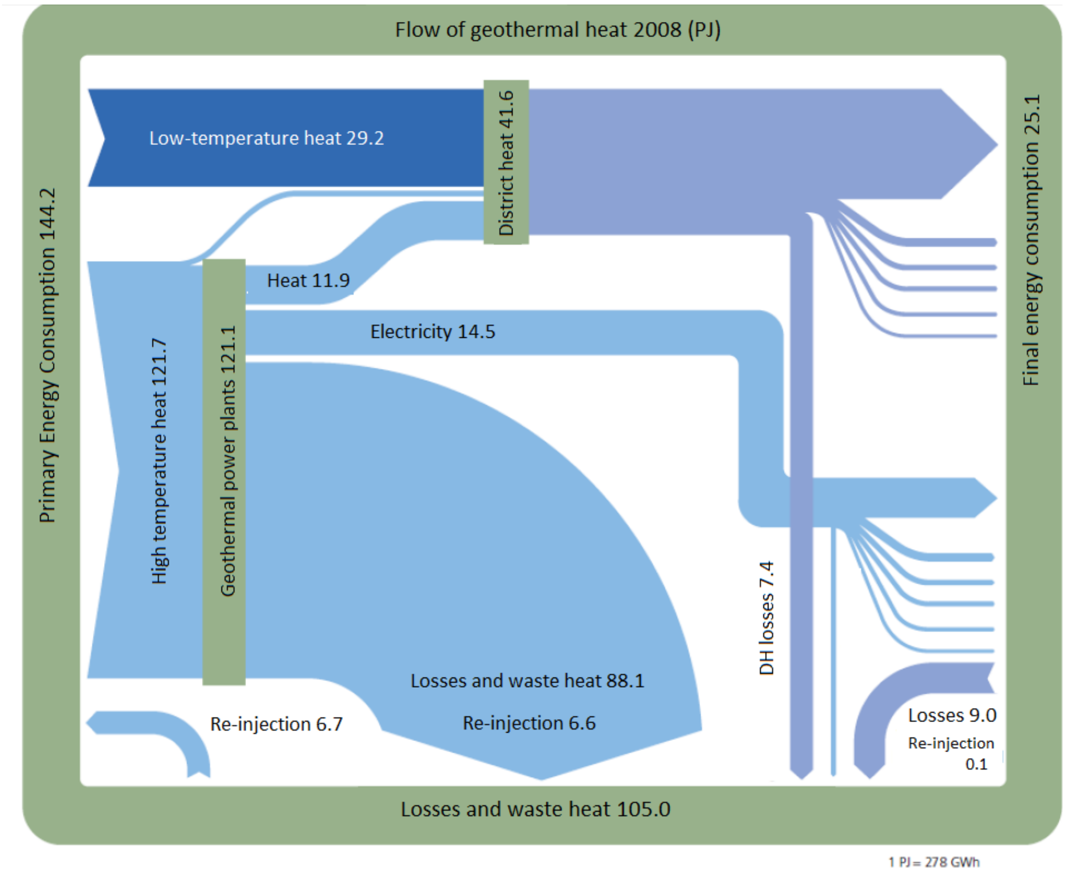


Figure 9: Flow of geothermal heat in Iceland for the year 2008 (adopted from [74]).

Figure 9 above shows the flow of geothermal heat in Iceland for the year 2008 from extraction to utilization. It can be seen that geothermal heat is divided into either high- or low-temperature geothermal heat. High temperature geothermal heat is used for power and heat production while low temperature geothermal heat is used only for district heating. Some of the high temperature geothermal heat is also used for district heating purposes. The production of district heat can therefore be divided in two parts;

I. Production of district heat from CHP plants using high temperature geothermal heat.

II. Production of district heat from district heat boilers using low temperature geothermal heat.

Figure 9 aggregates all units that have use the same fuel, i.e. units that use high- or low temperature geothermal heat. Thus all units that utilize high-temperature geothermal heat can be viewed as a single CHP plant for the purpose of the analysis. In reality though, not all power plants that utilize high-temperature geothermal heat are CHP plants.

The primary fuel consumption of geothermal heat is shown on the left side of Figure 9 and the end consumption is shown on the right side. The amount of waste heat and losses are shown on the bottom of the figure. It can be seen from this that the total district heat produced was 41.6PJ (11.6TWh) for the year 2008. This is the consumption of the district heat boiler which is fuelled both by low- and high temperature geothermal heat. The losses in the district heating network are shown as 7.4PJ (2.1TWh) which is a loss of around 18%. The losses from the CHP unit are therefore in this figure allocated fully to the power production and no losses are assumed to be allocated to the heat production in the CHP unit. The figure shows also the wasted/unused heat from the utilization phase of 9.1PJ (2.5TWh). This unused heat is not returned to the power plant but is released to the sea or into the ground.

As can be seen in Figure 9, around 70% of the geothermal heat is wasted or not utilized. This has to be considered extremely high amounts of waste heat. This is due to the fact that high temperature geothermal heat is primarily used for power production with a fuel efficiency of only 12%.

2.3. Electricity Demand and Production

The total *demand for electricity* for the year 2010 can be seen in table 2-3 along with the consumption for industry, residential- and tertiary sectors. The table shows that the total consumption for the year 2010 was 59.7 PJ (16.6 TWh) (extracted from [12]). Industry is by far the largest consumer of electricity with a total demand of more than 50 PJ (13.8 TWh). The residential sector and the tertiary sector each uses less than 5 PJ (1.4 TWh) each. The contribution of each of the sectors to the total energy demand can be seen in Figure 10.

2-3: Electricity demand in Iceland in different sectors for the year 2010

Electricity demand	Electricity *(PJ)*
Industrial sector	53
Residential sector	3
Tertiary sector	4
Total electricity demand	**60**

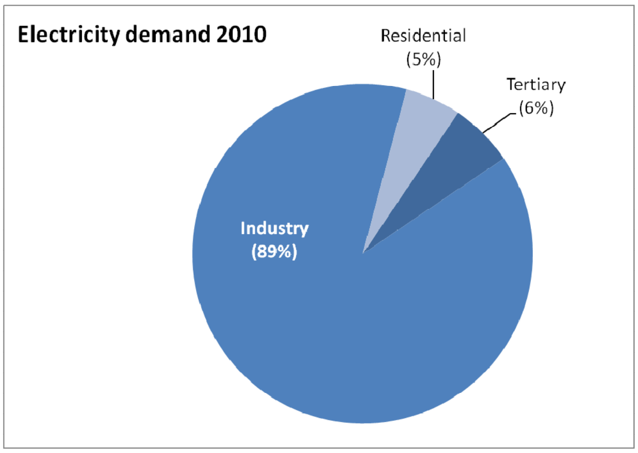


Figure 10: The share of industrial, residential and tertiary of the total electricity demand for the year 2010.

From the figure it can be seen that industry uses around 89% of the total energy demand in Iceland. The residential sector uses 5% of the total demand and the tertiary sector uses 6%. This high consumption of electricity within the industrial sector is unique and is due to a high penetration of energy intensive industries compared to the population of Iceland. These industries import and process raw material which then is exported and not used in Iceland. This is considered beneficial for the industries since the electricity prices are low in Iceland and the industries are guaranteed long term contracts of 20 years or longer [28]. The existing contracts that have been made with various energy intensive industries can be seen in Figure 11 below. The contracts that are made for these energy intensive industries are specified in terms of annual energy consumption and the power demand for a fixed number of years.

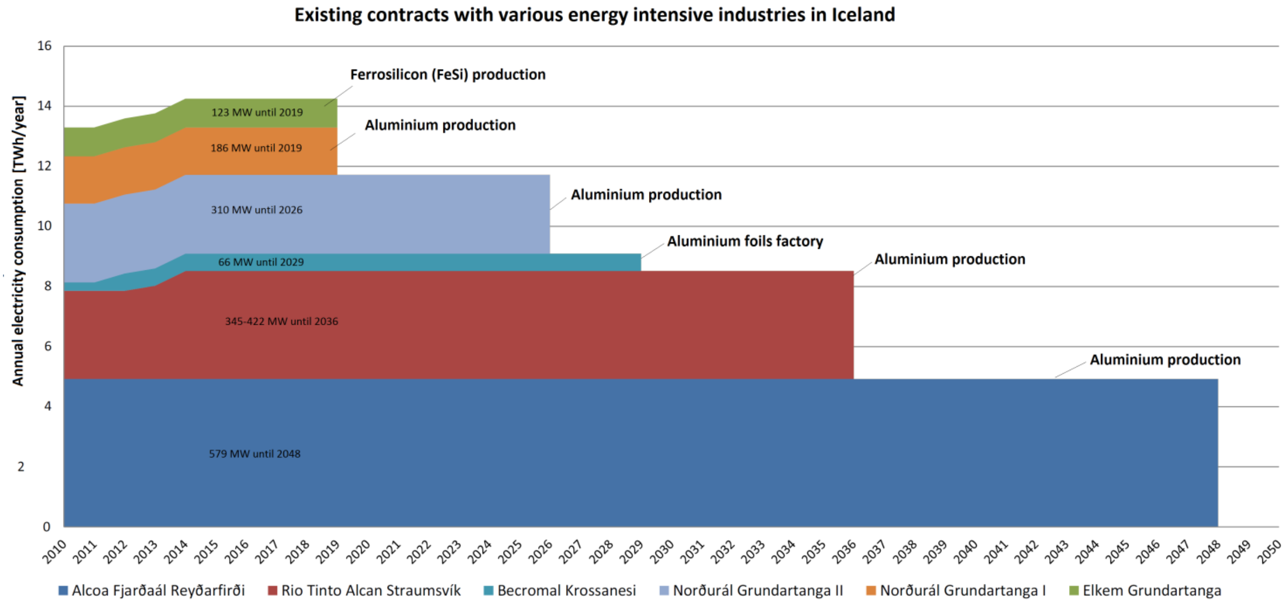


Figure 11: Existing contracts with energy intensive industries (adopted from [28]) .

Aluminium factories are the largest consumers of electricity and consumed 73% of the total energy demand in the year 2010 [10]. These aluminium factories are in operation around 8500 hours of the year and are therefore in operation day and night all year around with only few exceptions. The full-load hours for each type of energy intensive industry are shown in table 2-4 and the total power demand for these industries is around 1600MW[8].

[8] Assuming that all of the industries have peak demand at the same time at some point during the year.

2-4: Contracts made with existing energy intensive industries in Iceland for the year 2010 (adopted from [12])

Energy intensive industries	Annual electricity demand *(TWh/year)*	Total power demand *(MW)*	Full load hours *h/year*
Aluminium factories	12.1	1434	8430
Ferrosilicon factories	0.9	125	7440
Aluminium foil factories	0.3	52	5000
Total demand	**13.3**	**1611**[9]	**-**

The *electricity in Iceland is produced* by hydro power plants and by geothermal power plants. Table 2-5 shows the total installed capacity for each conversion technology and the total generation. **The installed power capacity in Iceland was 2579MW in the year 2010 and that the total generation was 17059GWh** (61.4 PJ) [10]. The total amount of electricity generated by hydro power plants was 12597 GWh (16.1 PJ) and geothermal power production was 4465 GWh (45.3 PJ) [10]. The full-load hours for each type of technology are also shown in table 2-5.

The hydro power units have the highest share of the total electricity production or 74%. The geothermal power plants produce 26% of the total generation (see Figure 12). Only a small fraction of the installed capacity is diesel generators and is used for backup generation and for electricity production on remote islands with no access to the power grid. This backup generation is however less than 0.1% of the total electricity production and is omitted in this study. Nearly all of the electricity generation is therefore produced by renewable energy resources that are found locally.

2-5: Installed capacities and electricity generation in Iceland for the year 2010 (adopted from [10])

Capacities	Installed capacity *(MW)*	Electricity generation *(GWh)*	Full-load hours *(hours/year)*
Hydro power plants	1883	12592	6687
Geothermal power plants	575	4465	7765
Other	121	2	0
Total	**2579**	**17059**	**-**

[9] Assuming that all of the industries have peak demand at the same time at some point during the year.

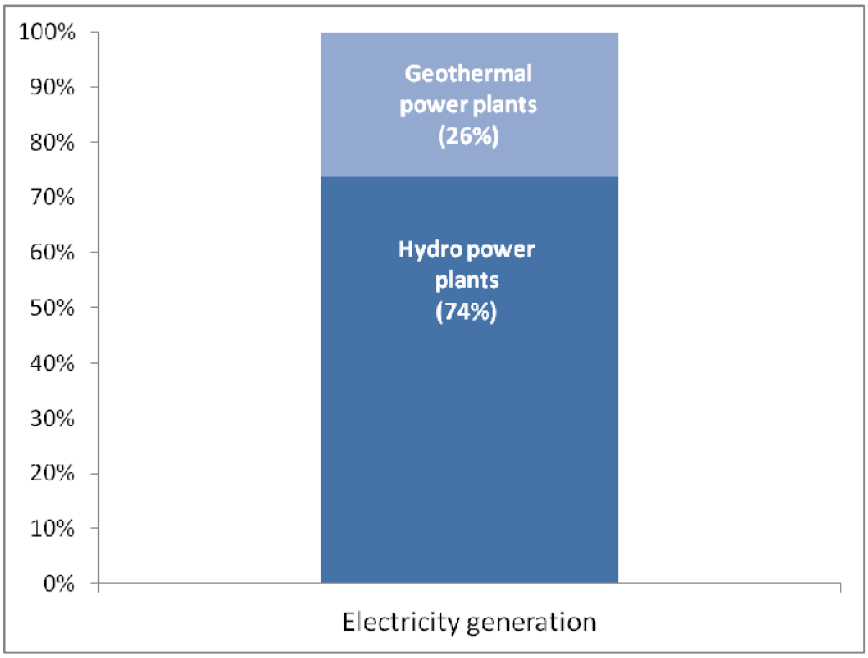


Figure 12: Contribution of geothermal power plants and hydro power plants to the total electricity generation in Iceland for the year 2010.

The historical development of the total electricity generation for Iceland is shown in Figure 13. It can be seen that the electricity generation in Iceland has experienced a boom in the past decades and has experienced some six fold increase in a time span of 40 years. This rapid growth can be explained by the introduction of energy intensive industries. In only 5 years from 2005 to 2010, the annual electricity generation increased from 8.6 TWh to 17 TWh which is an increase of around 95% [11]. Due to the small energy system in Iceland (around 2500 MW of installed power capacity), the introduction of energy intensive industries has more effect on the total system than it does on larger energy systems with a larger annual electricity generation. The increase in electricity generation from 2005 to 2010 is for example a result of an increase in production of two aluminium factories only. One of these factories expanded its aluminium production[10] capacities in the period while the other factory[11] was commissioned in 2007 [17]. It is therefore evident that the introduction of new energy intensive industries (or expansion of existing production capacities) can lead to drastic changes on the Icelandic electricity generation and could enforce the need for investments in new power capacities.

[10] The aluminum factory that expanded its production capacities is Norðurál (Grundartanga) which increased its annual production capacities of aluminum from 90 ktons/year in 2005 to a production of 278 kton/year in 2009 [61].

[11] The other aluminum factory is Alcoa Fjarðaál which was comissioned in 2007 and had a annual production of aluminium of around 350 kton/year [62].

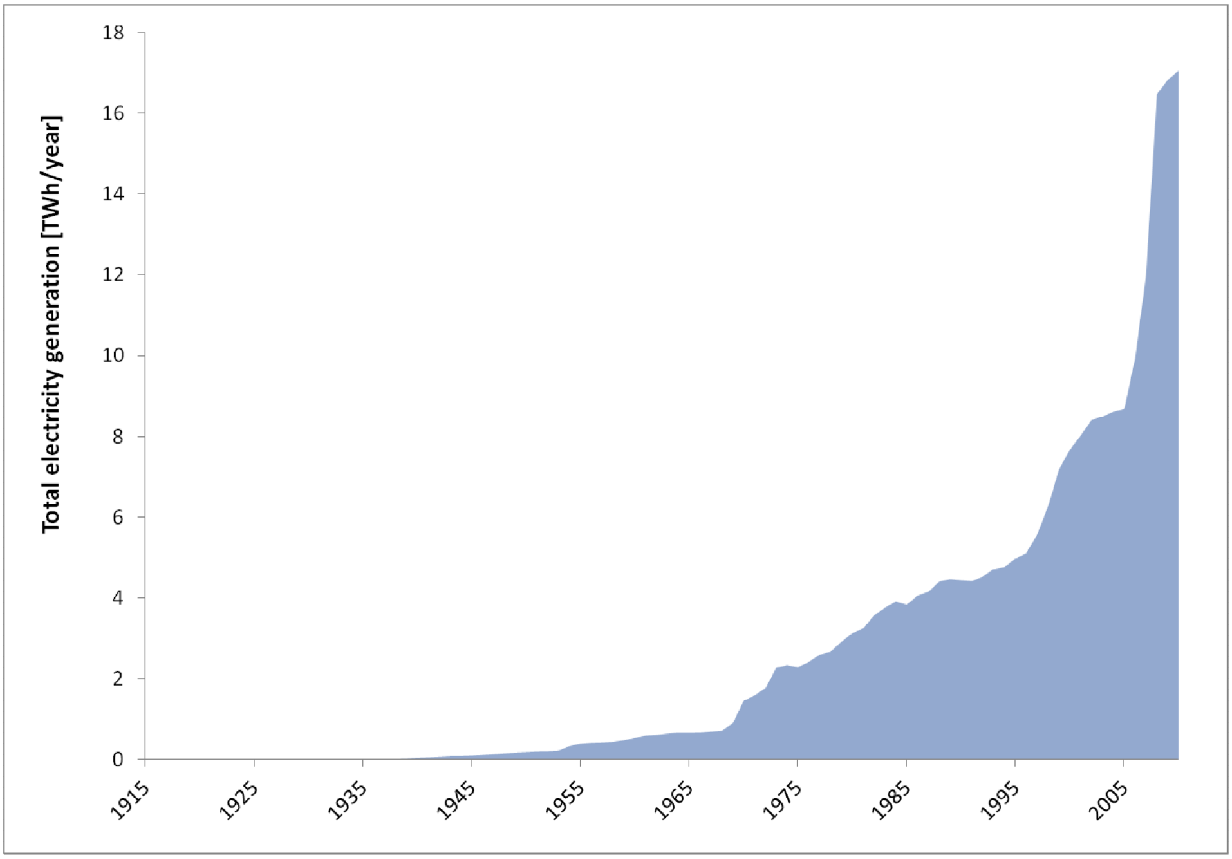


Figure 13: Historical development of the electricity generation in Iceland [11]

The electricity generation for the year 2010 can be seen in Figure 14 below. **Geothermal power plants operate as base load plants and the hydro power are used to supply the peak load**. With the high share of the power production being used for energy intensive industries (with high utilization level), the fluctuations in the power generation are low compared to the installed capacities. This can more clearly be seen in Figure 15 which shows the relationship between the (accumulated) power production and the full-load hours of the power plants. This duration curve is almost horizontal which means that the power plants in Iceland operate almost all year around to meet the demand from energy intensive industries.

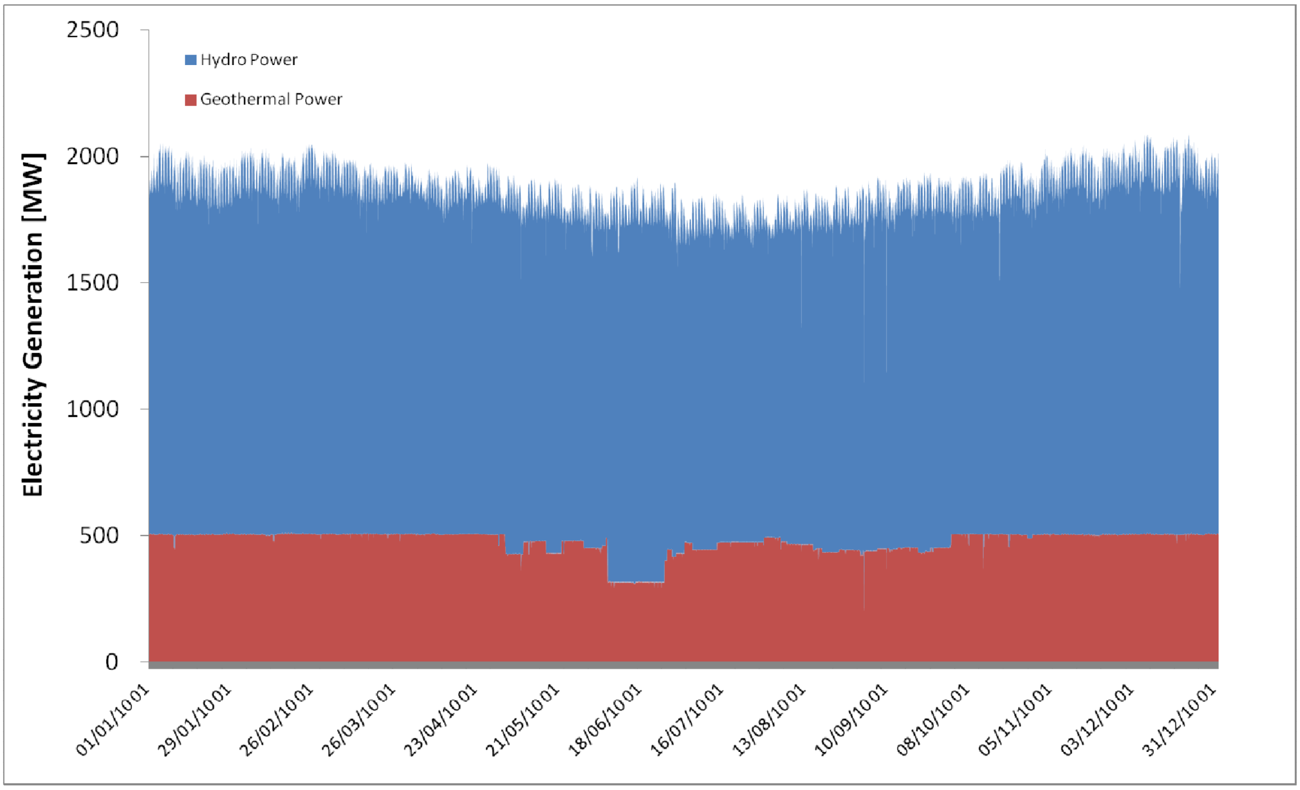


Figure 14: Hourly electricity generation for the year 2010 [18]

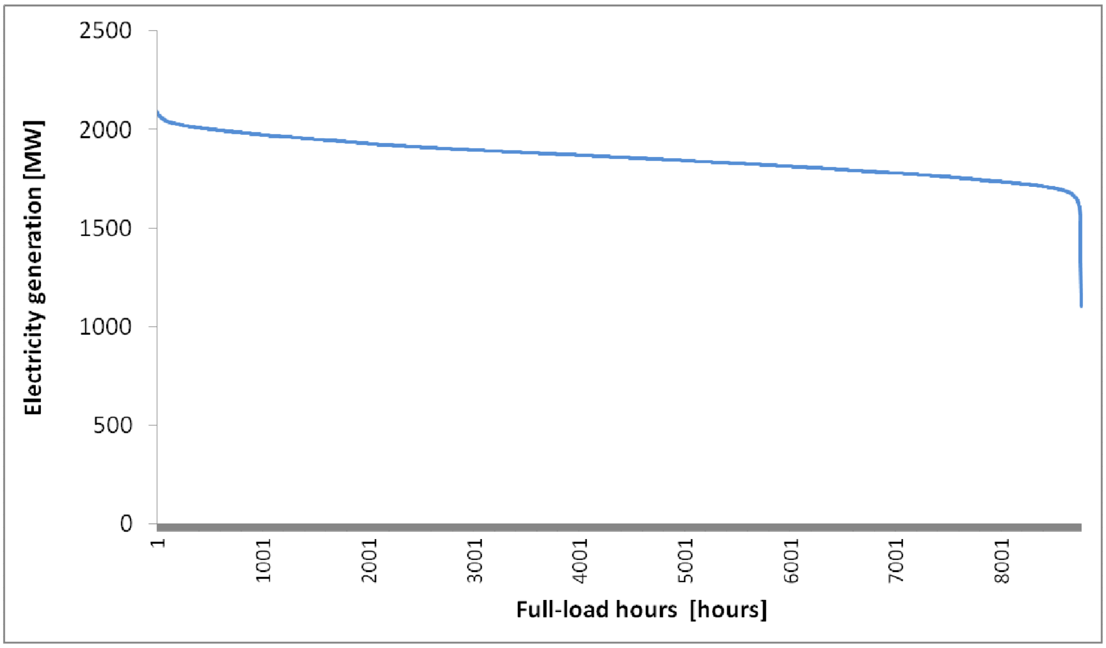


Figure 15: The generation duration curve for Iceland in the year 2010 (adopted from [18])

From Figure 14 it can be seen that the geothermal power plants operate on a constant power output of around 500MW while the hydro power plants are producing electricity at around 1500MW. With the installed capacities of 1883MW for the hydro units as shown in table 2-5, the hydro units are not fully utilized and could therefore produce more if the needed. This is under the assumption that the inflow of water to the reservoirs is not a limiting factor for the production. **This unused hydro generation for the year 2010 was around 4000GWh or around 450MW of power capacity**.

2.4. Power Transmission and Losses

Being an isolated island in the north-Atlantic ocean, Iceland does not exchange electricity with other countries. The electricity transmission system can be seen in Figure 16 and the system uses high voltage overhead lines with a voltage level up to 220kV. Energy intensive industries are distributed across the country and are indicated by a square in the figure. The transmission system has the highest density around the capital city in the south-western part of Iceland where around where most of the population lives. The density does however not indicate where the electrical load in the system is the highest since the electrical load is mainly connected with the energy intensive industries which are spread across the country. From the figure it can be seen that the demand from energy intensive industries is mainly in the south-western part of Iceland and the north-eastern part of Iceland.

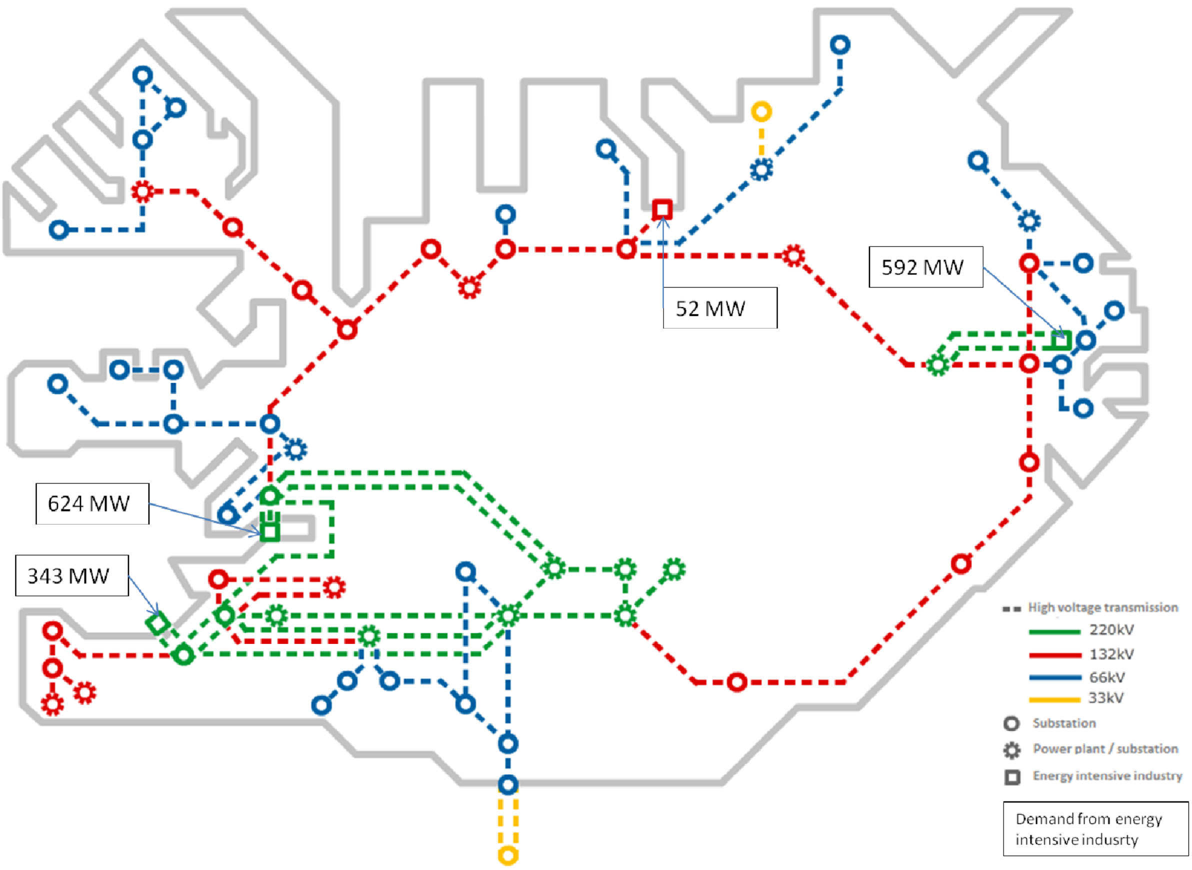


Figure 16: The transmission system in Iceland [10]. Demand from energy intensive industries is also shown (values inherited from [12]).

The arrangement of the electrical network from production to consumption in Iceland is shown in Figure 17 below. Energy intensive industries receive their electricity from the transmission grid directly while other users receive energy from the distribution grid. Power plants of less than 7MW do not feed electricity into the transmission system but directly to the distribution grid. The losses in the system were 2.84% for the year 2010 which involves losses both in the transmission grid and the distribution grid[12].

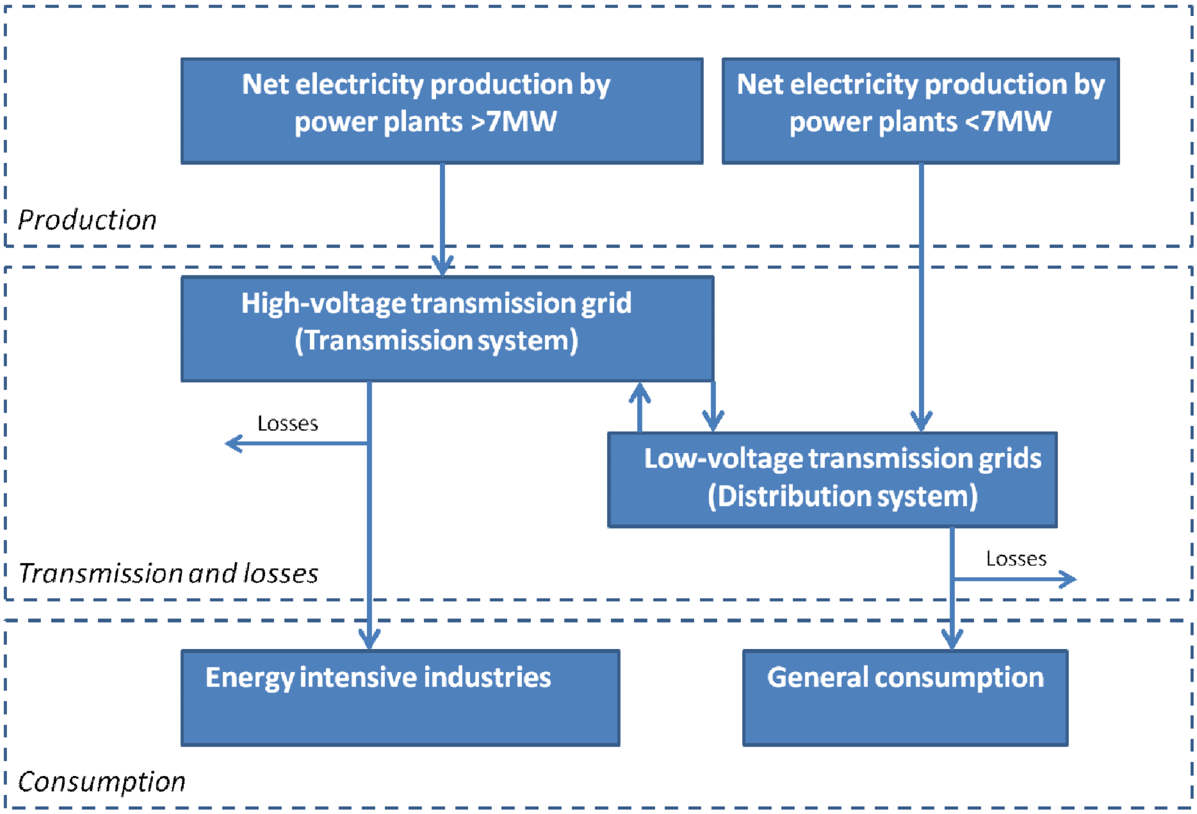


Figure 17: Electricity network arrangement in Iceland divided on production, conversion and consumption of electricity (adopted from [17]).

[12] For the year 2010, transmission losses were 330GWh and losses in the transmission system were 155GWh (extracted from [12]). Therefore with a production of 17059 GWh the losses are (155+330)/17059 = 2.84%.

3. Future Options for Iceland

As discussed in previous sections, Iceland produces its electricity by using local renewable resources of hydro and geothermal heat. These resources are considered abundant in Iceland and can easily be used to supply the Icelandic population with all of its electricity and heat demand. The introduction of energy intensive industries in Iceland has had large impacts on the energy system and the society in the past few decades and new power plants have been built to meet the demand of those industries. In this section, some of the options facing Iceland are listed and the governmental policies that have been laid out on energy are discussed.

A forecast of the electricity production in Iceland from the year 2011 until the year 2050 is shown in Figure 18 below. The forecast is done by the National Energy Authority of Iceland and is based upon assumptions on population, number of households, the quantities of produced goods for chosen industries and economic growth [12]. An important fact about this forecast is that it **does not account for the entry of *new* energy intensive industry** but only the energy demand from existing industries. The existing contracts made with energy intensive industries (shown in Figure 11) are assumed to be extended throughout the projection period. The reason for not including new energy intensive industries in the projections is that the introduction is dependent on political decision and the business environment each time, making it extremely difficult to predict for. Historical data shown in Figure 18 demonstrates this and shows the sudden changes that the energy production in Iceland has experienced in the past few years. The energy production increased drastically in these years due to, as discussed in section 2.3, the introduction of a single aluminium power plant and the increased production capacity of another aluminium smelter. Thus the introduction of energy intensive industries can lead to big changes on the total electricity generation in Iceland and is a fact due to small size of the system compared to the size of the introduced industries.

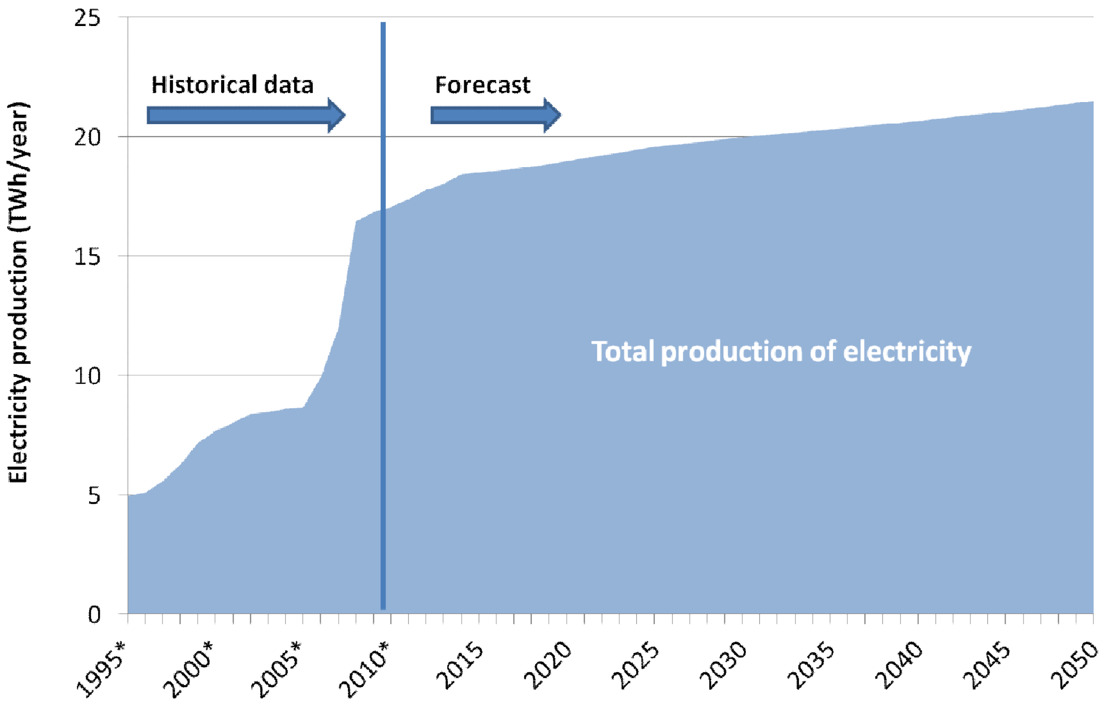


Figure 18: Forecast of electricity consumption from 2010 to 2050 based on historical data (adopted from [12]).

In Iceland, increased demand from energy intensive industries in Iceland is expected in the next decades and table 3-1 lists some of these industries. The industries listed have not been introduced yet but have either settled a contract on power sale or are in a planning phase of getting such contracts. The total demand from these industries is around 200MW[13].

3-1: Examples of industries that could be introduced in Iceland in the next years. Some contracts have already been made while others are in planning phase.

Industry	Electricity demand *(GWh/year)*	Power demand *(MW)*	Reference
Silica factory in Helguvík[14]	550	65	[12]
Silica factory in Húsavík[15]	456	52	[64]
Methanol production from flue gas[16]	-	50	[12]
Sodium Chlorate factory[17]	-	40	[12]
TOTAL		**207**	

The introduction of new aluminium factories is not shown in the table but some projects are already under discussion[18]. With a total production of around 800.000 tons of aluminium per year in Iceland [65] and an energy demand of 12.1TWh/year as shown in 2-4 for the aluminium industry, the energy demand is around 15MWh per ton of aluminium produced. Therefore for an aluminium factory with an annual production of 250.000 tons, the total power demand is around 400MW. This sized aluminium factory is comparable with the three existing aluminium factories that already are in operation in Iceland.

With the introduction of the new industries listed in 3-1 and a single new aluminium factory with a production capacity of 250.000 ton, the power demand is therefore likely to increase by 200-600MW and the annual electricity demand is likely to increase by around 1-5TWh[19].

---

[13] Assuming that the industries operate on constant power supply, i.e. operate all year around.
[14] Main shareholder is Global Speciality Metal (USA) and contracts have been made on power sale from 2013-2015 [12].
[15] Main shareholder is PCC (DE) and contracts have been made on power sale from 2015-2030 [64].
[16] Feasibility studies are to be laid out on this in cooperation with the company Carbon Recycling [12].
[17] Statement on power sale interest has been made with the company Kemira (FI) [12].
[18] New aluminium factories that are in development are e.g. aluminum factories in Bakki and Helguvík.
[19] Assuming that aluminum factories operate 8500 hours/year and others industries 7000 hours/year.

Along with the increased demand from energy intensive industries in Iceland, the option of installing a **transmission cable between Iceland and Europe** has been discussed for a while and is now considered both technically and economically feasible [66]. The project is still in development phase but agreements have been made between energy ministries in Iceland and the United Kingdom (UK) where participants confirm their interest in the project. The contract was signed on the 30th of May 2012 and can be found in [67]. The agreement involves general cooperation in the energy sector and on the transmission cable the agreement states:

> "*The Participants express their willingness to explore the possibility of developing an electricity interconnection between Iceland and the UK, including the legal and regulatory issues*" [67]

The transmission cable would be around 1200km long and would be the largest submerged transmission cable in the world, thereby exceeding the 580km long NorNed cable which links Norway and the Netherlands [66]. This project is, according to the national power company of Iceland (Landsvirkjun) considered more feasible in recent years due to increased power prices in Europe compared to Icelandic prices and due to favourable support schemes in the European Union for renewable energy in relation to the 2020 objectives [15]. Landsvirkjun states that the cable under discussion **would have a power capacity of 700MW** [15] but no agreements have been made on that matter. For energy intensive industries, Landsvirkjun offers long term contracts with prices that are 30-50% cheaper than average prices in Europe or around 43 USD/MWh [15]. The price of the electricity sold to the UK has not been decided but could be comparable with the price given to energy intensive industries. The type of contract made between the two countries is uncertain but given the history of contracts made with the energy intensive industries (shown in Figure 11), a long term contract on delivered annual electricity and on power level has to be considered likely. Assuming that the transmission cable operates 8500 hours/year like the aluminium factories, the annual demand would be around 6TWh. This is around 30% increase in the electricity production in Iceland for the year 2010. Landsvirkjun mentions that feasibility studies could be done by the year 2015 and that the cable would take 5 years to produce and install, therefore **making it possible to start operation in 2020** given that the project will be accepted [66].

Based on the previous discussion, the energy demand in Iceland is likely to increase significantly in the next years if both energy intensive industries and a transmission cable to Europe will be introduced to the Icelandic energy system. The question then remains if the energy resources in Iceland are large enough to be able to support this development and whether such utilization of resources can be considered sustainable in the long term. Both the resources of geothermal heat and hydro power are considered renewable but the utilization of these resources can indeed be considered unsustainable (see discussion in section 4.

The exploitation of the geothermal heat and the water resource for electricity production can have negative environmental impacts on the surrounding environment and has recently started a discussion on the importance of minimizing those impacts. The most recent example of those impacts is the commissioning of a large hydro power plant in 2007 of 690MW [41]. In order to supply an aluminium factory for its electricity demand, this power plant needed a total of 57km^2 of unexploited land for its water reservoir. Geothermal power plants can also have negative environmental impacts and the production of electricity (and heat) using high temperature geothermal fields is known to emit substances such as Sulphur dioxide (H2S) and has also been linked with an increased frequency of earthquakes in surrounding towns[20]. New power plants that utilize water or geothermal heat will always have some environmental costs and a simplification of the problem at hand can be shown in Figure 19. With increased demand for electricity, investment in new capacity is needed at higher environmental costs. These costs in the figure shown to be divided in three groups;

- Existing power capacity at non-retrievable/acceptable environmental costs (shown in green).
- Investment in new power capacity at moderate environmental costs (shown in yellow).
- Investment in absolute maximum capacity at unacceptable environmental costs (shown in red).

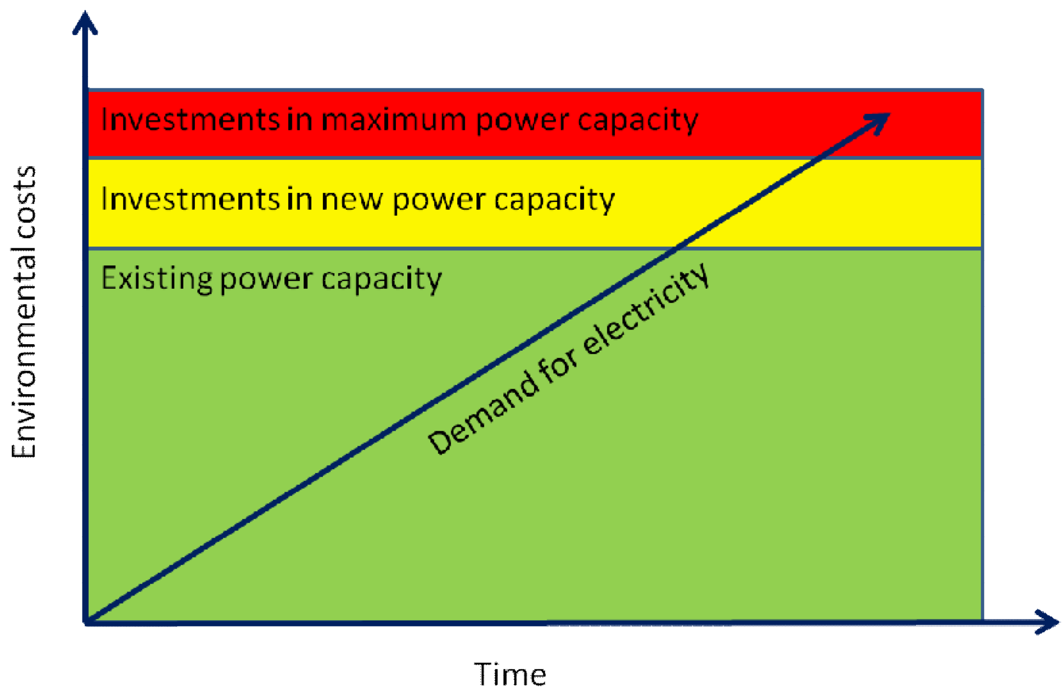


Figure 19. Increased demand for electricity enforces the need to invest in new power capacity with consequent environmental costs.

In the year 1999, the Icelandic government launched project entitled "**Master Plan for Hydro- and Geothermal Resources in Iceland**" [25]. The intention of the project was to get an overview of these two energy resources and to rank proposed geothermal and hydro power plant options based on economic, environmental and social factors. The project was divided in two phases with the first one lasting from 1999-2003 and the second one from 2004-2011 [26]. First phase considered 43 proposed hydro and geothermal power options while the second phase considered 84 options (of which 14 options that had been proposed in first phase) [27]. The number of options considered in the second phase of the master plan can be seen in table 3-2 below. In total the energy generation from these

[20] These earthquakes are considered to be due to the re-injection of geothermal brine back to the ground which serves as to maintain the pressure in the geothermal field.

proposed power plants is 47.5 TWh/year which is around three times more than the electricity production was in Iceland in the year 2010. The comparison between the existing capacity and the capacity of projects evaluated in the master plan is shown in Figure 20 and it can also be seen that more of the electricity generation evaluated in the master plan is produced by geothermal power plants than hydro power plants.

3-2: Proposed power plant options evaluated in the second phase of the Icelandic master plan for hydro and geothermal resources (adapted from [27]).

2nd Phase of the Master Plan	Proposed Projects *(number of projects)*	Potential Power Production *(GWh/year)*
Hydro Power Plants	40	17500
Geothermal Power Plants	44	30000
Total	**84**	**47500**

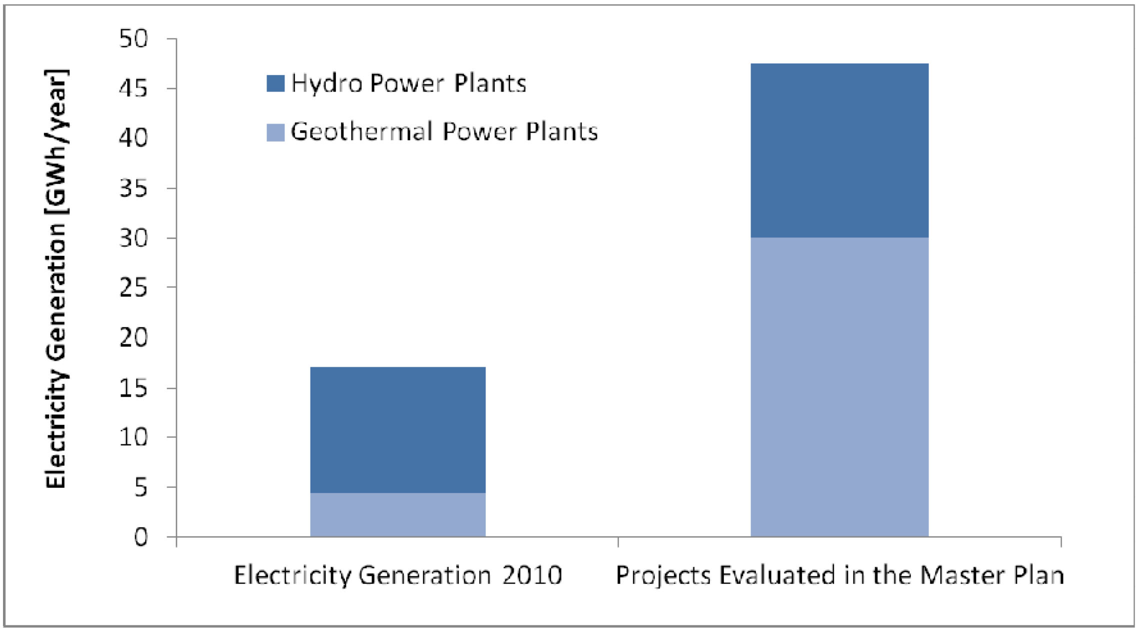


Figure 20: Comparison between the electricity generation in the year 2010 and the proposed power plants evaluated in the 2nd phase of the Icelandic master plan for hydro and geothermal resources.

The proposed projects (power plant options) evaluated in the master plan are ranked and categorized in three groups that describe whether they can be executed or if the projects are considered to have too large negative impacts on the environment and the society and thus should not be executed. These groups are shown in Figure 21 below and the result from the master plan is summarized in table 3-3. It can be seen that **the electricity production from geothermal and hydro resources is evaluated to be around 30TWh/year which is then the maximum production from these resources**. This grouping of projects is however not finite and some are expected to be moved from the waiting list to utilization group and vice versa. This discussion is ongoing in the parliament and a recent update from that discussion is that two proposed hydro power plants will be moved from available projects to the waiting list and thereby lowering the electricity generation from approximately 12TWh/year (group C in table 3-3) to around 8.5TWh/year [70].

Available projects	Waiting list	Not available projects
Power plants that can be built and thus fulfil the criteria of sustainable development.	Power plants where impacts on the economy, environment and the society needs further investigation before being built.	Power plants that impose too large environmental impacts and should not be built.

Figure 21: Projects evaluated in the Master Plan were grouped into three main categories shown here (adopted from [69])

3-3: The maximum annual electricity production available in Iceland from geothermal and hydro resources as estimated in the master plan (adopted from [28]). The geothermal power plants assume 50 years of utilization of the geothermal resource.

	Hydro *GWh/a*	Geothermal *GWh/a*	Total *GWh/a*
Electricity Generation			
Installed capacity 2009 (A)	12300	4600	16900
Being built 2011 (B)	585	738	1323
Evaluated in 2nd phase of Master Plan			
Available for utilization (C)	2741	9170	11911
Waiting list (D)	6008	3098	9106
Not available	7280	4059	11339
In total	16029	16327	32356
Within areas of protection	465	13616	14081
Total electricity production (A+B+C)	**15626**	**14508**	**30134**

A general **energy policy**[21] for Iceland was published in the year 2011 and is meant to be used as a foundation and guideline for all political decisions made on the matter in coming years [71]. The policy covers a broad range of measures that are important for ensuring a sustainable development within the society, economy and the environment in Iceland and its main objective is the following:

> *"That the energy is managed and utilized in a sustainable way to the benefit of the society and the population of Iceland"* (translated from [28]).

Other set of goals described in the energy policy include the security of supply for consumers and that the energy resources are utilized with respect for the surrounding environment, its nature and its distinctive features [28]. Furthermore should the utilization of the (common) energy resources found in Iceland result in revenues for the population of Iceland[22] and managed in a way to maximize the benefits of the society as a whole [28].

Both the *Master Plan for Geothermal and Hydro Resources* and the *Energy Policy* are extremely important steps towards a society that does not "compromise the ability of future generations to meet their own needs while meeting the need of the present" (as stated in the definition of sustainable development and laid out by the United Nations [72]). The *need* of the present and the future generations is debatable and can range from utilization of energy resources to preserving these resources and therefore leaving them unexploited. Both options are to be valued in order to attain a widespread acceptance in the society on these matters and the master plan and the energy policy are measures that can somewhat be used for that purpose. Other measures and tools that can be used is the concept of scenario analysis which will be introduced and discussed in section 5.

4. Energy Resources and Potentials

As discussed in previous sections, water and geothermal heat are the two energy resources that are used for electricity production in Iceland and the potentials for both of these resources are considered large. Both of these resources can be considered renewable and therefore could in practice supply the energy demand for Iceland for a long period of time. Excessive utilization of the resources can however be considered unsustainable and can therefore, at a certain point, impose negative impacts on the society and the environment. In this section, the nature of the two energy resources of water and geothermal heat is described in brief and the reason why and how their utilization can be considered unsustainable is discussed. The potential for electricity production from geothermal- and hydro power plants in Iceland is discussed from a sustainability perspective and the potential for other resources than water and geothermal heat is discussed briefly.

The large amount of **geothermal heat** found in Iceland is explained by its location on the Mid-Atlantic ridge which defines the boundary between the Eurasian and North-American tectonic plates [19]. These two tectonic plates move apart around 2cm each year, making Iceland unique in the way that only few places on earth where you can see and active spreading ridge above sea level. Due to its location the volcanic activity is high and geothermal energy is more easily accessible than in most other countries. In this regard

[21] The policy is entitled „Orkustefna fyrir Ísland" and can be found in reference [28] (in Icelandic).
[22] This can be achieved in many ways, e.g. by reducing costs for electricity.

it is important to distinguish between low-temperature geothermal fields and high-temperature geothermal fields. Low-temperature geothermal fields are often defined as those in which a temperature of 150°C or lower is obtained at depths of 1km and high temperature fields where the temperature at the same depth is 250°C [20]. Temperature fields in the interval 150°C-250°C do exist and are considered to be either connected to existing high-temperature fields or to be the remains of old temperature fields which have cooled off in time [20]. A map of known geothermal fields is shown in Figure 22 below in total there is around 200 low temperature fields and around 30 high-temperature fields. It can be seen that geothermal fields are widespread in Iceland and that the high-temperature fields are located in bedrock layers younger than 0.8 million years while the low-temperature geothermal fields are found in older rock layers. High-temperature geothermal fields are used as an energy source for power and heat production while low-temperature geothermal fields are used mainly used as an energy source for district heating.

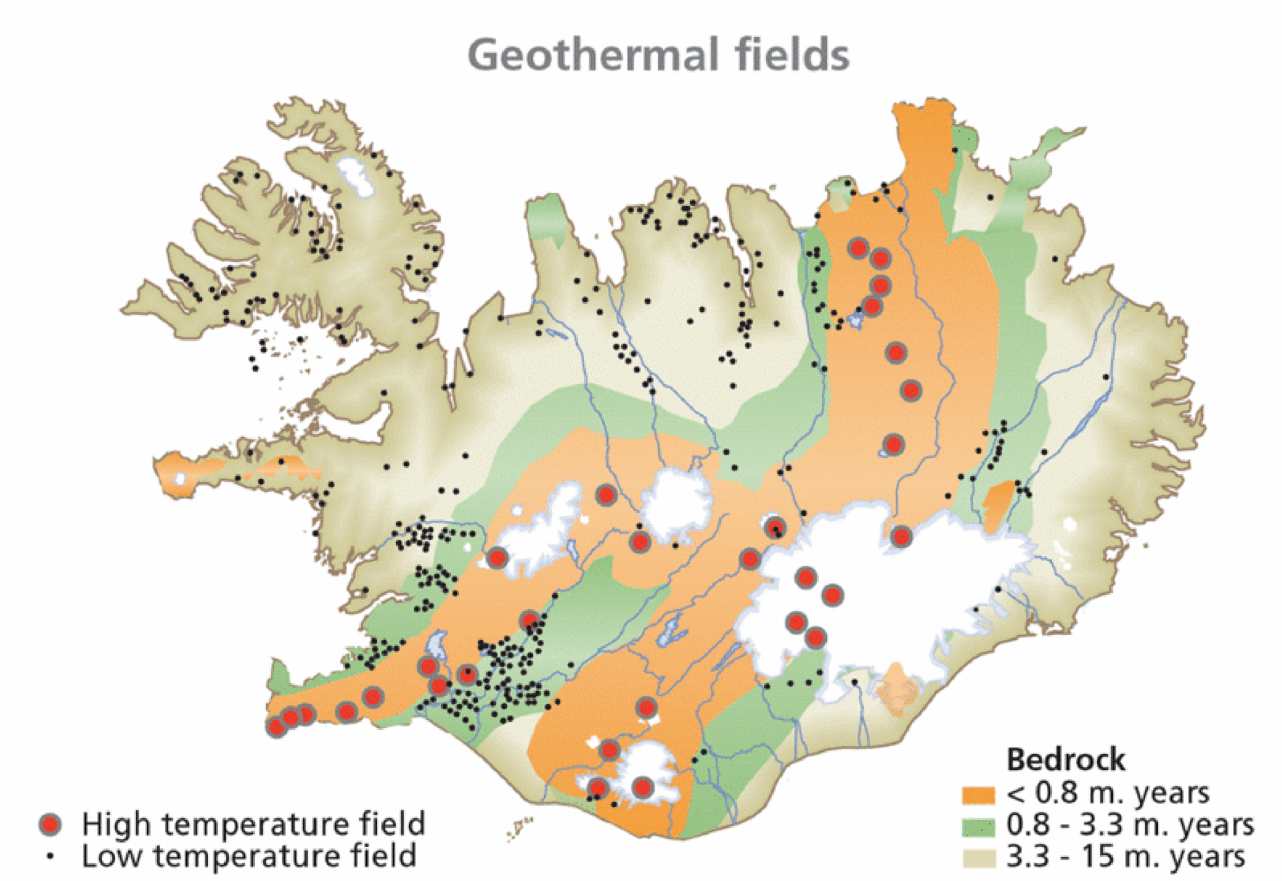


Figure 22: Map of high and low-temperature geothermal fields in Iceland. High-temperature fields are found in younger bedrock layers while low-temperature fields are found in older rock layers away from the ridge [19].

High- and low temperature geothermal fields are different not only for the sake of temperature differences but also in the way the energy is transferred to the surface as can be seen in Figure 23 below. High-temperature geothermal fields obtain most of their energy from magma intrusions whereas low-temperature geothermal fields get the energy from the earth crust through degradation of radioactive substances in the core of the earth [21, 22]. Geothermal heat for both of types of geothermal fields is transferred to the surface and to the underlying rocks through convection of ground water and through conduction of heat from the rock layers below. The geothermal heat source therefore consists of two types of heat sources; heat flux through convection or conduction and the storage of heat in surrounding rock layers. These heat sources obtain their heat at different rates and the renewability of the sources is thus also different. The definition of geothermal heat as a renewable energy resource can be debated since the heat stored in the rocks can be renewed so slowly that it can be considered non-renewable and therefore a *finite energy resource* [73]. This applies especially to the part of the heat storage that is renewed by heat conduction.

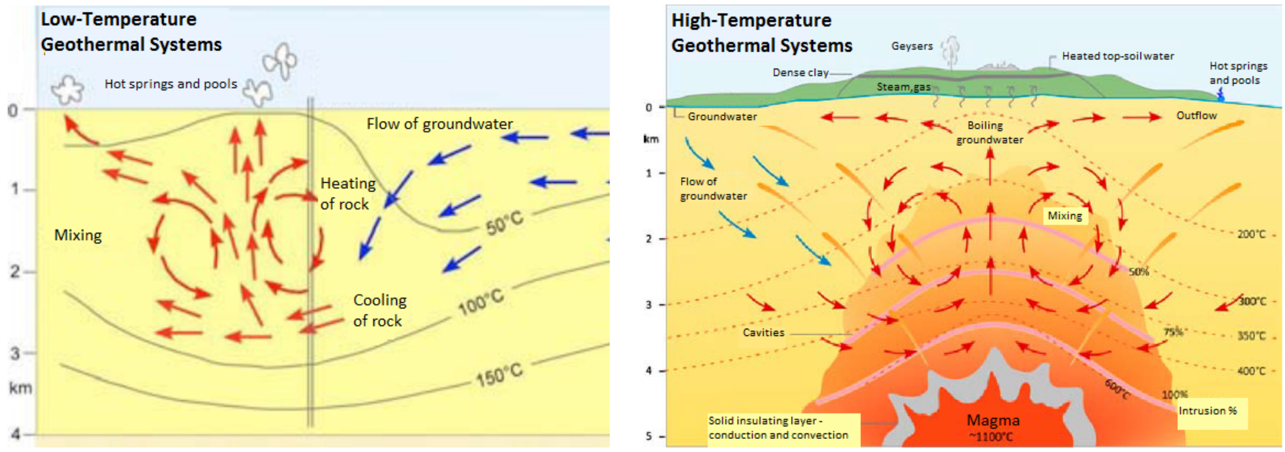


Figure 23: A comparison between low-temperature geothermal systems (to the left) and high-temperature geothermal systems (to the right) (adapted from [20]).

As can be seen in Figure 23, a circulation of groundwater occurs in both high- and low-temperature geothermal fields. In the vicinity of a heat source, cold ground water heats up and ascends to the surface due to the loss of density. If this hot groundwater is not extracted for power and heat production, it will cool down and descend where the circulation pattern will continue and a state of balance is maintained. During power and heat production from geothermal fields, this balance can be disrupted and can in some cases lead to the cooling of the geothermal fields if the extraction of heat becomes too excessive. In practice it is difficult to estimate in advance the maximum extraction from geothermal fields that have not been exploited before since each geothermal field has its own complexity. Therefore the geothermal power plants often installed in small steps and with a low power capacity so that the response of the system can be monitored. When extracting steam from the geothermal fields, the pressure in the fields drops and can result in lower groundwater levels and increased inflow of cold water into the geothermal field. The pressure drop in the geothermal field and the cooling due to the inflow of cold water can somewhat be reduced by injecting unused water from the power plant back into the ground and this method has been used in Iceland.

In Iceland, a **sustainable utilization of geothermal heat** is defined as the utilization level (electricity generation) that can be sustained for *at least 100 years* [20]. The level of utilization is different for each geothermal field but the concept of sustainable utilization is illustrated in Figure 24 below. The maximum electricity generation is indicated by E0 and any generation above that level is considered unsustainable while generation below E0 is considered sustainable. E0 is not known in unexploited geothermal fields but can be approached by increasing the capacity of geothermal power plants in small steps. In this way the risk of excessive extraction can be minimized and can therefore also result in a longer lifetime of the geothermal field.

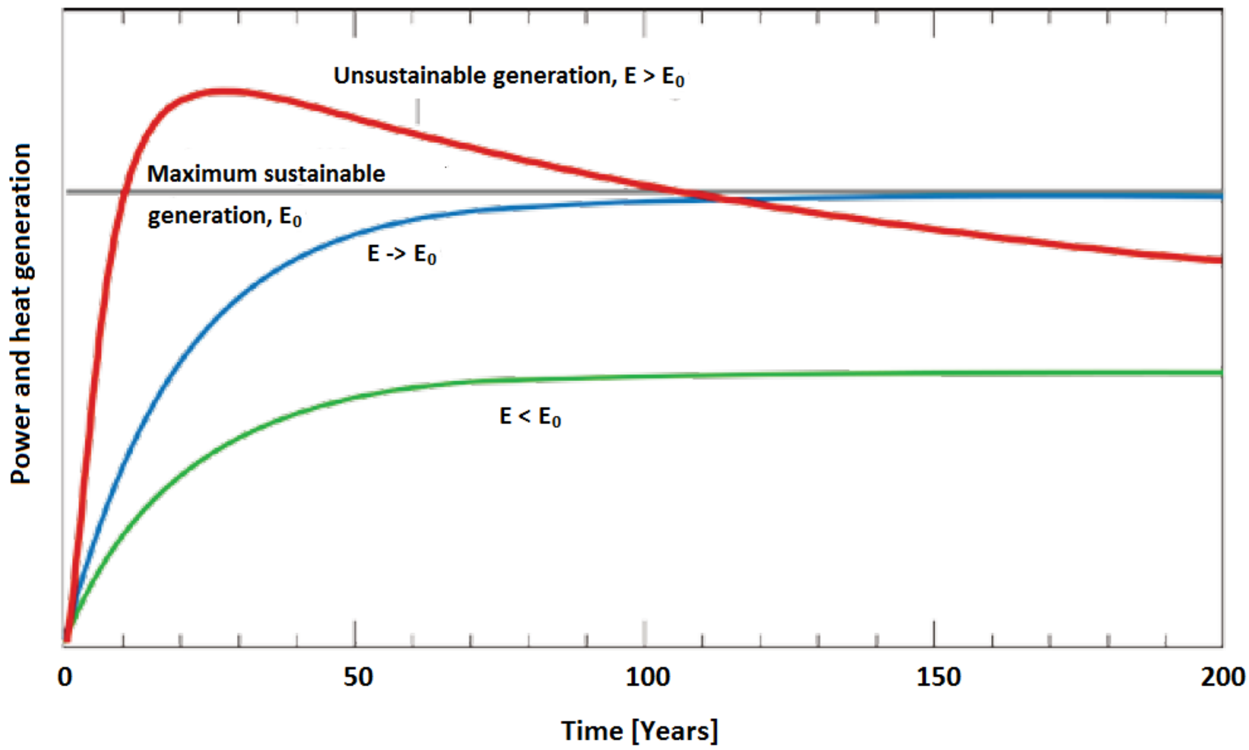


Figure 24: Sustainable utilization of geothermal heat (adopted from [20])

In Iceland, hydro power plants produce most of the electricity and the **large amounts of water** flows in rivers from the highlands of Iceland towards the sea. The water flowing in the rivers is renewable and is a part of the hydrological cycle which is originated and driven by solar energy. A large part of Iceland is covered with glaciers and many of the most powerful rivers are consequently glacial. The flow of water in the rivers is therefore dependent on the volume of the glaciers and the precipitation level and both seasonal and annual changes in the flow is observed. The glaciers melt to some extent in the spring- and summertime and the flow of water in the glacial rivers changes accordingly. With a lower demand for electricity in the summertime in Iceland than in the wintertime, the water is most often stored in reservoirs during the summer and then discharged in the wintertime when needed [73].

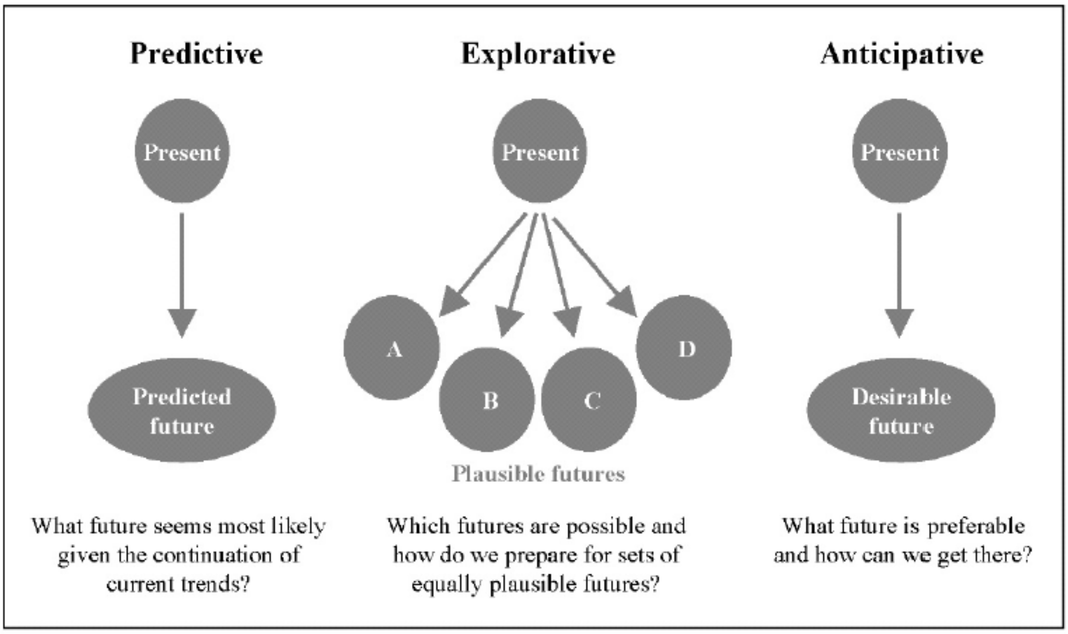
Like with the geothermal heat in Iceland, a discussion on the **sustainable utilization of water for power production** is ongoing and this discussion can be linked with the fact that hydro power plants (with or without reservoirs) normally impose large impacts on the surrounding environment. These impacts can be both positive, negative and somewhere in between and the power plants can impact the economy and the society in similar ways as they impact the environment. Although the water resource is renewable, its utilization *can indeed become unsustainable* if it compromises the ability of future generations to meet their own needs. The utilization of the water resource itself cannot be considered limited since only free flow of water is harnessed for the electricity production. The needs of future generations is not known but building a hydro power plant (or a geothermal power plant) might affect e.g. the tourism industry in Iceland and whether power production and tourism industry can be synchronised is hard to say.

The total energy production that can be produced from hydro and geothermal resources was discussed in section 4 in relation to the master plan for hydro and geothermal resources and is shown in table 3-3. In this table, geothermal heat is assumed to be utilized for 50 years while a sustainable utilization of geothermal heat should last at least 100 years as discussed above. In this study, a 50 year utilization of geothermal heat is used in accordance to the master plan and therefore the potentials for geothermal- and hydro power are as shown in the table with a maximum electricity generation of around 30 TWh/year.

Other resources for use in electricity production other than geothermal heat and water have only been exploited to a minimum level in Iceland and the potentials have not been fully estimated to date. Wind potential is expected to be large and wind turbines are likely to be installed when it becomes economically competitive to the hydro- and geothermal power plants. Biomass for power production is limited and is likely to be used for transportation rather than electricity production. Same applies to biogas which currently is being recovered from land-filled waste in small amounts and upgraded for use in transportation. Iceland does not have coal or oil resources as of today. Potential solar power production has not been estimated and is not likely to be of special interest in near future. The potential from tidal energy has been somewhat studied in Iceland and both the technologies of a tidal barrage and tidal stream turbines have been discussed in that respect.

5. Energy Scenario Analysis

Predictions for future energy demands are extremely difficult since political decisions play a big part in this development as mentioned in section 3. One can compare it to the *butterfly effect* where a decision made today will completely change the future. The dynamics of the world at times of globalization makes the situation so complex that even not the most advanced computer models can foresee and the longer the time span, the greater errors are introduced. This is especially important in small energy systems like the Icelandic one where large investments in new power plants can greatly influence the total demand. In this context it is important to introduce the concept of energy scenarios, of which there is often a distinction made between three types of scenarios; *predictive* scenarios, *explorative* scenarios and *anticipative* scenarios and Figure 25 shows the difference between these scenarios. In section 5.1, the energy scenarios for Iceland are created based on the future options for Iceland discusses in section 3. These scenarios are then used in the model simulations that are discussed in section 6.



Source: Baumgartner and Midttun (1987a), Godet and Roubelat (1996), Dreborg (1996) and Robinson (1982)

Figure 25: A Comparison between predictive, explorative and anticipative scenarios.

Predictive scenarios assume business as usual behaviour with current trends extrapolated into the future based on historical data. As mentioned before, these predictive scenarios can be subject to inaccuracy when political decisions play a part of the energy system. This can therefore result in a future of unexpected outcome which is hard to prepare for.

Explorative scenarios are used to explore different plausible scenarios and how to cope with each one of them. These scenarios are used to prepare for different futures in order not to get caught by surprise in the end.

Anticipative scenarios are scenarios where the desirable future is agreed upon and ways are found of how to get there in steps. These scenarios are different from both predictive and explorative scenarios in the way that they offer the chance to have something to say about the future. The process of visualizing the future and pathways toward that future is often termed back-casting and can be applied to many things including energy systems (see Figure 26).

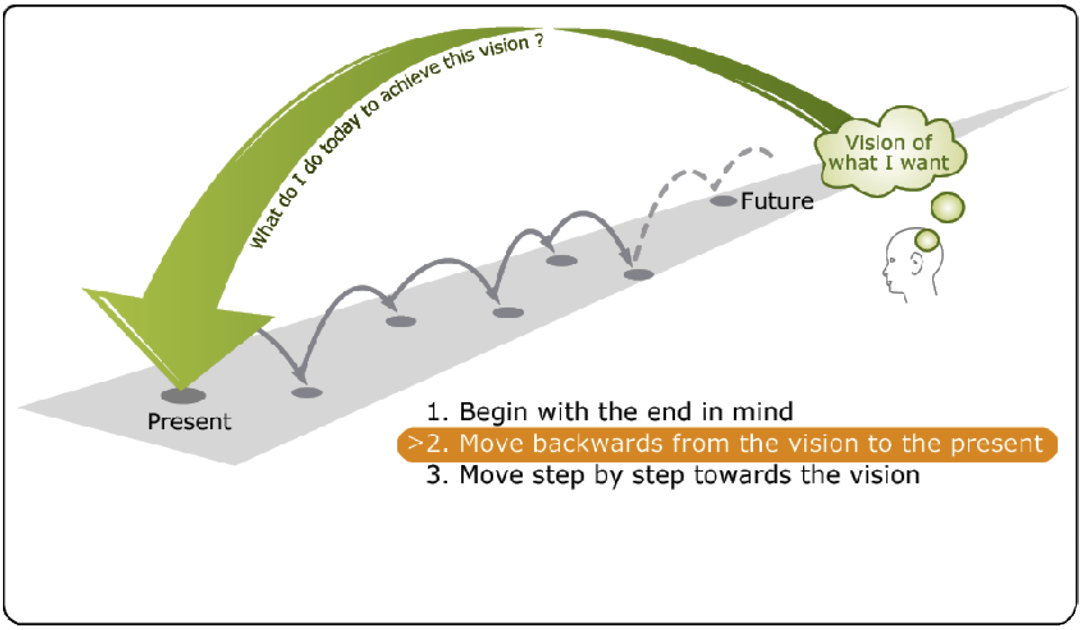


Figure 26: Backcasting is used to create anticipative scenarios [5]

5.1. Creating Scenarios for Iceland

In order to analyse the future perspectives discussed in section 3, scenarios are created which then are used in the modelling (section 6). As mentioned previously, there are three main categories of scenarios that can be created; predictive, explorative and anticipative scenarios. Of those three categories, focus will be on predictive and explorative scenarios in this thesis since these are the two types of scenarios that are of most relevance given the future options for Iceland discussed in section 3. Ultimately, anticipative scenarios should be created for Iceland since they offer the advantage of having more to say on the future of the energy system and can be compared to the transition of being a passenger in a car to being the driver in control[23].

Growing demand for energy intensive industries and the suggested transmission cable to Europe discussed in section 3 are two options that Iceland is currently facing and both of these options could have large impacts on the Icelandic energy system. Whether the system can support both of these options is a question worth asking and for that purpose, the explorative scenarios are created. Especially it is important that the energy system can be operated in a sustainable way in compliance with the policies that already have been laid out by the Icelandic government (discussed in section 3).

In this thesis, one **predictive scenario** is used for Iceland and it is based on the electricity forecasts until the year 2050 made by the National Energy Authority in Iceland. This forecast was discussed in section

[23] For this project, an attempt was made to create **anticipative scenarios** for Iceland and was done as a part of the project “Nordic Energy Technology Perspectives” (NETP). Scenarios were created using the energy modelling tool STREAM, which is an open-source model developed in Microsoft Excel and can be used to give a quick insight into the energy system in question [24]. The model was adjusted in a way so it resembles the Icelandic energy system in terms of energy production, energy demand for different sectors of the society and energy for transportation. These scenarios are not used in this thesis but the STREAM model served its purpose to give an overview of the energy system in Iceland and could in practice be developed further and used for scenario analysis.

3 and from this forecast the total electricity demand for each year until 2050 electricity was extracted. This scenario is hereby referred to as the "*Base-Case*".

Two **explorative scenarios** are created for this project and are to be compared to the base-case discussed above. Explorative scenarios, as explained in section 5, explore plausible futures and can be used to prepare for the problems that can arise in the future with the introduction of a transmission cable between Iceland and Europe and with a further expansion of energy intensive industries in Iceland. The future options were discussed in section 3 and among the most important questions that need to be answered for these two options are:

1. What are the impacts on the Icelandic energy system by the introduction of a transmission cable which can support a power transmission of 700MW?
2. Can the Icelandic energy system support the transmission cable to Europe and at the same time support further expansion of energy intensive industries?

In order to answer these questions, two scenarios were created; Scenario "*Cable*" which is intended to answer question 1 and Scenario "*Cable and industry*", indented to answer question 2. For the first question on the transmission cable to Europe (scenario "Cable"), it is interesting to discuss the different ways of which the transmission cable can be operated. Linking the Icelandic energy market to energy markets in Europe can have both negative and positive effects on the Icelandic energy system depending on the type of contract made between the participating nations. Based on the previous history of contracts made with energy intensive industries (discussed in section 3), the contracts made are normally long term contracts on power supply to those industries, and the contract with Europe could in practice resemble those contracts. The electricity generation for the transmission cable would thus be rather **constant throughout the year with a fixed annual generation**.

Another option is to link the Icelandic market to the European market based on economical principles where electricity would only be generated when it suits the market, i.e. when **the cost of producing electricity is cheaper in Iceland than it is in Europe**. With the prices for the energy intensive industries in Iceland being 30-50% cheaper than prices in European markets (as published by the national power company, Landsvirkjun, and discussed in section 3), the transmission cable is likely to be in constant operation regardless of the two types of contracts are made. This does not need to hold true and can be analysed through the use of energy modelling tools such as BALMOREL which is discussed in next section.

A summary of the scenarios discussed in this section can be seen in Figure 27 below and these scenarios will be modelled and analysed in succeeding sections.

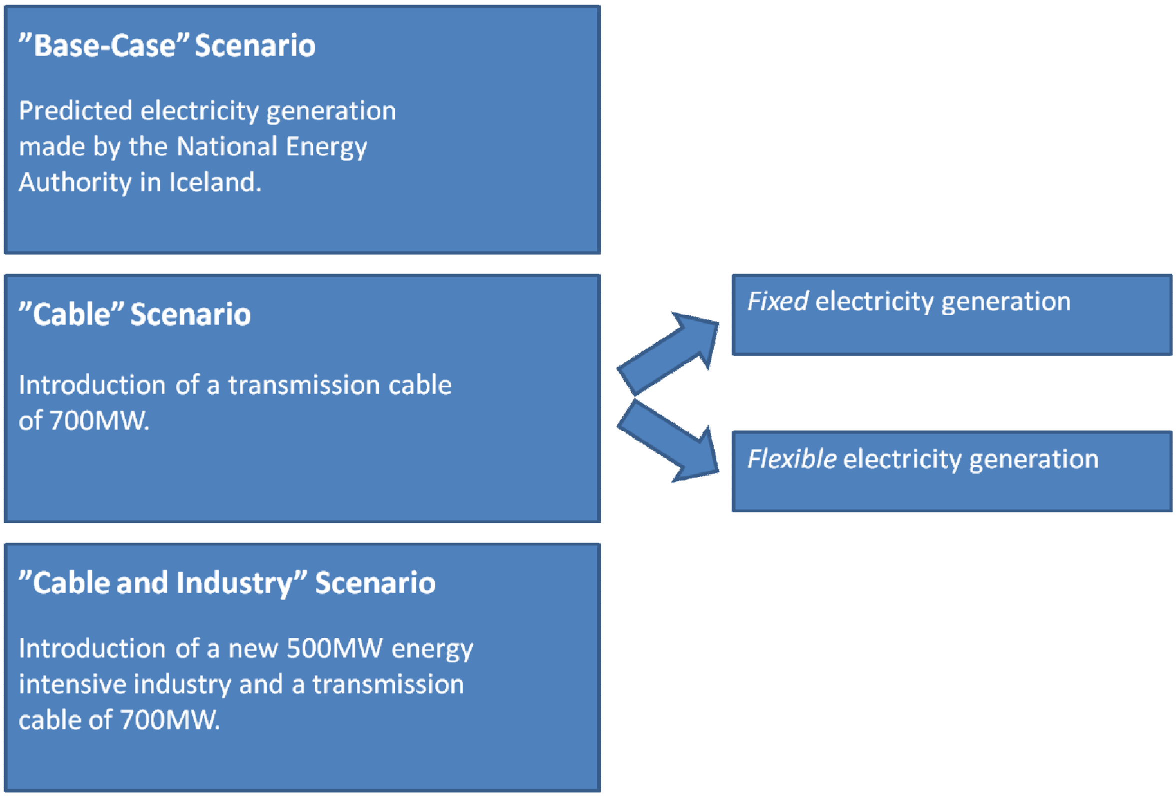


Figure 27: Scenarios to be modelled and analysed.

6. BALMOREL Optimization Model

BALMOREL is an energy modelling tool that originally was developed for the analysis of power and CHP sectors in the Baltic region [29]. The model has been developed under open source ideals since the year 2000 and is formulated in the GAMS modelling language [30]. BALMOREL can be downloaded from [31] and modified by any user depending on the application in question (a licensed version of GAMS is needed for running the model). Documentation is provided on code level [31], making the model transparent and indeed very flexible for a variety of applications. It has been used in projects in many countries including Denmark, Norway, Estonia, Latvia, Lithuania, Poland and Germany [31]. The type of analysis that has been laid forward by use of the model includes security of electricity supply, the role of flexible electricity demand, hydrogen technologies, wind power development, expansion of electricity transmission and the development of international electricity markets [31].

The BALMOREL model simulates and optimizes the operation of the energy system in question given a set of constraints [30]. The model objective is to minimize costs of running the energy system and it suggests the optimal operation of the energy system for a specified time horizon. The user specifies the subdivision of years into seasons and time steps. The seasons can be looked at as weeks of the year while the time steps can be looked at as the hours of the week. Other data and calculation results are given in relation to a geographical subdivision that depends on the study in question [30].

The Icelandic energy system **has not been modelled** and analyzed by the use of BALMOREL energy modelling tool before and this can partly be explained the fact that Iceland is an isolated system with no connections to other countries that have already been modelled. With the (possible) introduction of a transmission cable to Europe, the system cannot be considered isolated anymore and the interplay between the Icelandic energy market (energy system) and the European market becomes an interesting topic of discussion. By introducing Iceland into an optimization model such as BALMOREL, ideas such as a connection to Europe with a transmission cable could be discussed and argued more thoroughly and can give a better understanding of the effects that such a connection can have on the Icelandic energy system. In this thesis, **the Icelandic energy system will be implemented in the BALMOREL model** and the way this is done is described in this section. The functionality of the BALMOREL model is described in section 6.1 and the input data is described in section 6.2. The model criteria and objective is then discussed in section 6.3.

Building a model for Iceland in BALMOREL can be considered a long-term process and a constant updating of and revision of such a model is needed for the model to give the best representation of the energy system as possible. The work presented here can be considered a beginning of such a process and suggestions for further development of the model is given in section **Error! Reference source not found.**.

6.1. Model Functionality

The Icelandic energy system was implemented to BALMOREL by specifying the necessary input data and by adjusting the model for it to resemble Icelandic conditions. This section will elaborate on how this was done and what assumptions were made to make the model running. The BALMOREL model is a comprehensive model and a large part of the work was to understand the functionality of the model for the Icelandic energy system to be implemented in a logical way.

An illustration of the functionality of the BALMOREL model is shown in Figure 28. It shows a general representation of the type of data entering the model (model input), under what conditions (constraints) the model executes its calculations (model simulation) and what can be extracted from the model at the end of the simulation (model output). Based on this structure, data for Iceland was added to the model along with required adjustments in the BALMOREL GAMS code. The input data is discussed in section 6.2 and the model objective and constraints in section 6.3. The results from the simulations will then be discussed in section 7.

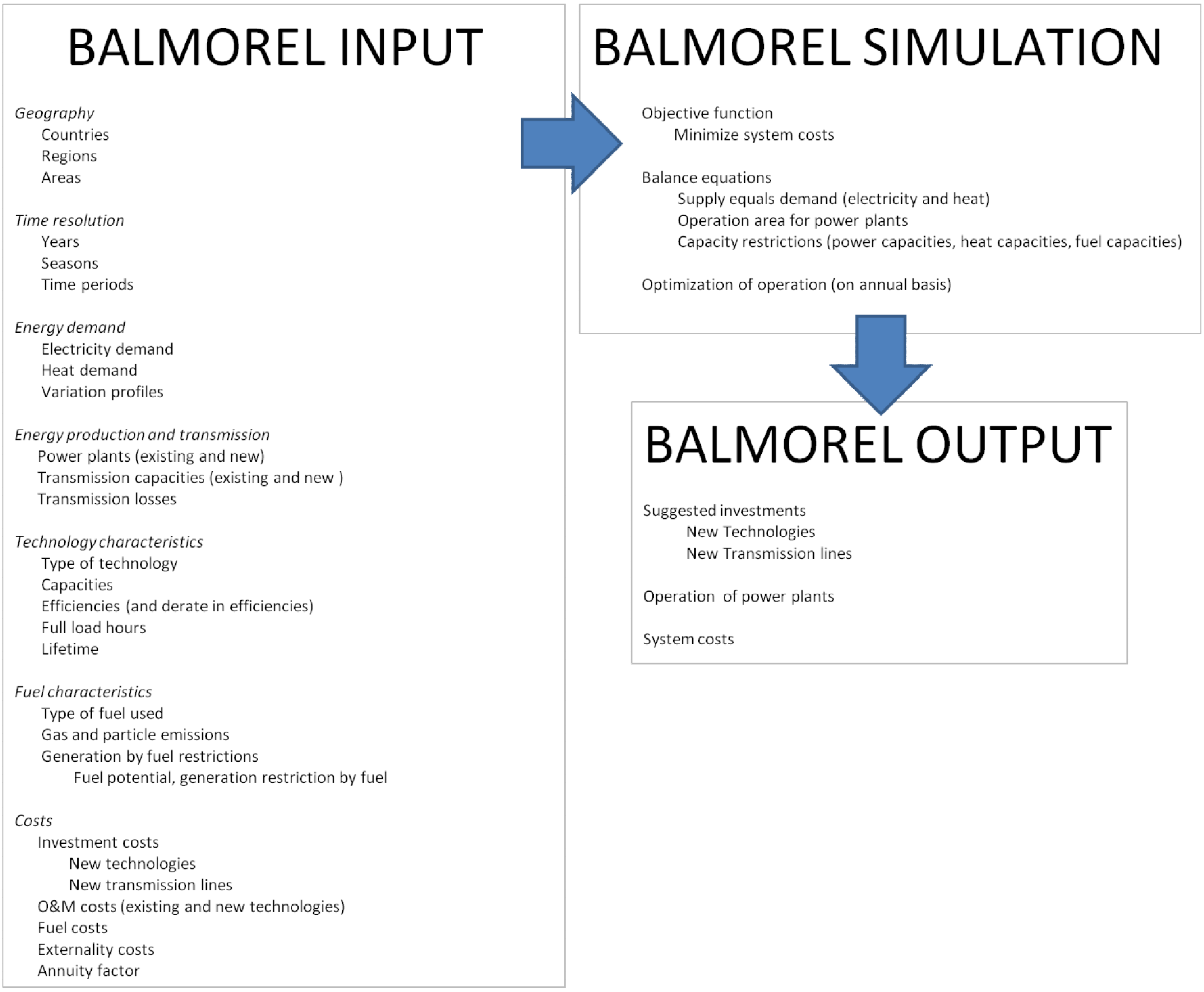


Figure 28: Schematic representation of the functionality of BALMOREL

6.2. Data Acquisition and Assumptions

The BALMOREL model requires large amount of data as input in order to run. During this project, some data was readily available for use while some assumptions were needed to be made for lacking data. These assumptions will be discussed in this section and since data is somewhat different between scenarios, this will be elaborated on as well. Iceland had not been implemented in the BALMOREL before this study and this section describes the main input data needed for the model to run. The model is a simplified version of the Icelandic energy system and improvements to the suggested model developed in this project is done in section **Error! Reference source not found.**.

GAMS modelling language distinguishes between different type of input data. *Sets* are the indices by which all data can be indexed over. This is an important distinction and allows for example technologies to be specified on geography level and efficiencies to be specified on technology level. The input files therefore can be either defined as sets or as data entry where numerical values are inserted. The data entry can be of different layout and is usually defined as *parameters* in the BALMOREL model meaning that the data is list oriented (vector oriented). Data can also be entered in the form of a *scalar* value (single element) or as a *table* value (more than two dimensions) but these forms of data entry is only occasionally used in BALMOREL.

6.2.1. Geography

In BALMOREL, countries are subdivided into regions which then are subdivided into areas. For the Base-case scenario, Iceland is assumed to consist of **one region and one area** as shown in Figure 29. For the scenario “cable and Industry”, a region was also specified for new energy intensive industries in Iceland. BALMOREL allows data to be specified either on country level, region level or at area level. Electricity demand is for example specified on regional level while the heat demand is specified on area level. This means that for each new region an electricity demand for that region needs to be specified and for each new area a heat demand has to be specified. The resolution of available data is therefore essential part of the decision of how to subdivide each country into regions and areas. During the course of this project, only aggregated numbers for the whole country could be attained and this limited the ability to allow further subdivision of Iceland into regions and areas. A more detailed geographical subdivision in Iceland could be a part of future development of the model when data becomes more detailed and more readily available.

In relation to the transmission cable to Europe (scenario “cable” and “cable and industry”), there was no need to specify UK as a new geographical entity. UK is not modelled in BALMOREL yet but was represented by other means (discussed in section 6.2.4).

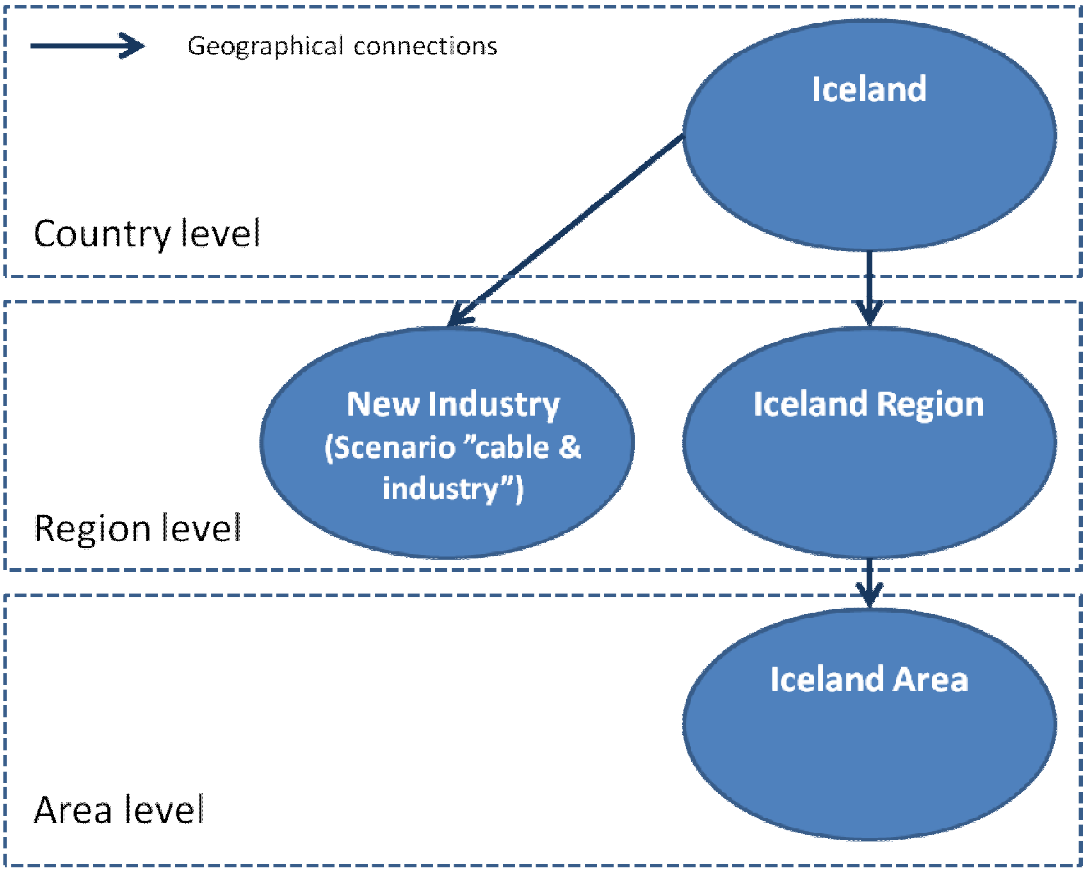


Figure 29: Subdivision of Iceland into regions and areas.

6.2.2. Time Resolution

Three years are simulated for all scenarios and these years are 2010 which is the base year, 2020 and 2050. Each year is divided into 52 weeks (the seasons) and each week is divided into 168 hours (time steps). This means that the year consists of 8736 hours instead of 8760 hours in a normal year. The model corrects for this by having each hour (time step) slightly longer than a normal hour. Some data is specified for each time step while some data is specified for each season. An example of data that is specified on weekly basis is the hydro inflow to reservoirs and example of data specified on hourly basis is electricity demand. The time resolution is the same for all scenarios and for all years.

6.2.3. Energy Demand

The main difference between the scenarios shown created for this study (and shown in Figure 27) is in the annual electricity demand until the year 2050. A comparison of the electricity demand is shown in Figure 30 below. For the "Base-Case", the annual demand is the projected demands done by the National Energy Authority of Iceland and is a somewhat cautious scenario where no new industry is included (see Figure 18). For the scenario "cable" a demand from the proposed transmission cable to Europe is added to the base-case demand for each year from 2020 when the cable is assumed to be installed. The assumptions here are that the **power demand from the transmission cable is 700MW** and that the cable has 8500 full-load hours, therefore having an annual demand of 5.95TWh. For the scenario “cable and industry”, increased demand from both the transmission cable and new energy intensive industries in Iceland is added to the demand in the base-case scenario. **The industry is assumed to have a power demand of 500MW** with 8500 full load hours per year. The annual electricity demand from new energy intensive industry is therefore 4.15TWh and this size of industry is comparable to the possible new industries discussed in section 4. The energy intensive industry is assumed to be introduced in the year 2015.

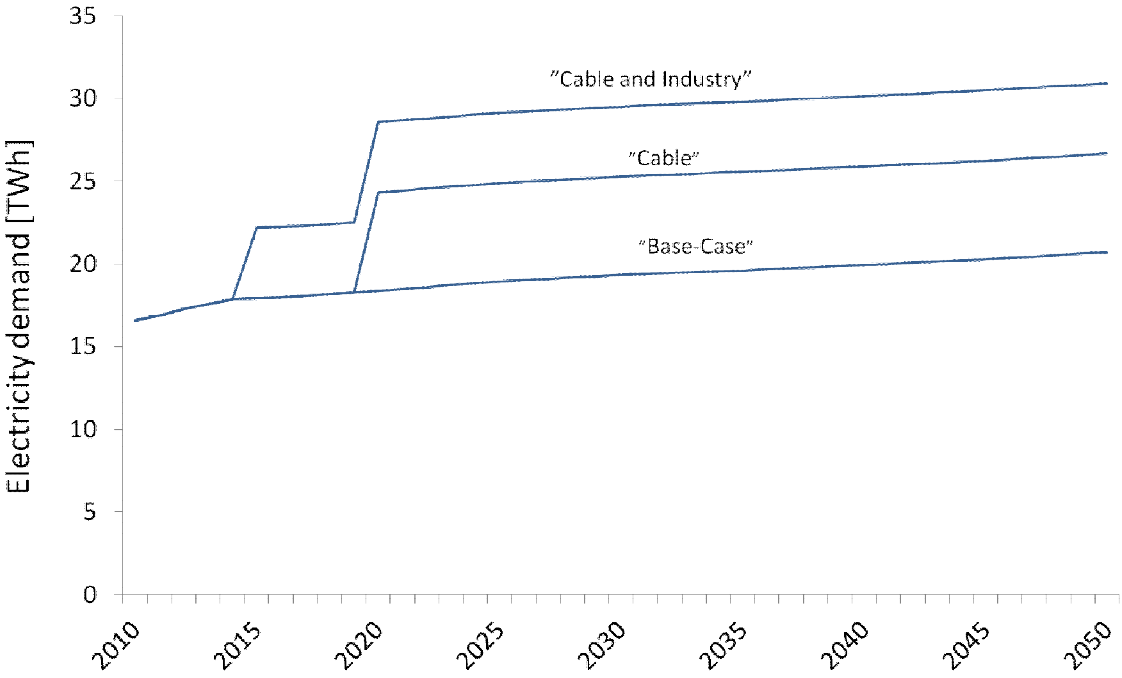


Figure 30: Comparison of electricity demand between the three studied scenarios

Variation of the electricity demand over the year is assumed the same for all three years in the simulation. The variation profile is given on hourly basis and is scaled from the year 2010 to the year 2020 and 2050 by the following equation:

$$Variation\ profile\ for\ each\ year\ [MW]\ \cdot Hours\ in\ a\ timestep\ [h] =$$

$$Annual\ electricity\ demand\ for\ each\ year\ [MWh/year]\ \cdot \frac{Variation\ profile\ at\ time\ step\ t\ in\ the\ base\ year\ [MW] \cdot Hours\ in\ a\ timestep\ [h]}{Sum\ of\ values\ in\ the\ variation\ profile\ [MWh/year]}$$

The variation profile for the electricity demand thus gives the relative size of each demand in relation to other time steps. From this equation the variation profile for the years 2020 and 2050 is generated. The peak load of the variation profile occurs in season 51 and time step 115 in the model which corresponds to a peak load in 21st of December between hours 18 and 19.

Heat demand for the year 2010 was included in the BALMOREL model of Iceland. Demand for other years was not used implemented in the model. Hourly variation for heat demand could not be obtained for Iceland in the year 2010 (or other years) and therefore another variation profile was used for the base year 2010. This assumption makes all analysis of heat demand difficult on hourly basis and was therefore omitted. It was furthermore assumed that heat demand could more easily be met than electricity demand given the great amounts of heat dismissed in the operation of geothermal power plants (see Figure 9).

6.2.4. Energy Production and Transmission

The electricity production, as modelled in BALMOREL, is done by 7 geothermal power plants and 15 hydro power plants. The list of existing power plants used in the BALMOREL model is shown in 6-1 below and is used for all scenarios created in this study. The total power capacity for geothermal units is 662.9MW and 1883MW for hydro units. These capacities are slightly different from the installed capacities shown in table 2-5 and the reason is mainly the increased capacity in Hellisheiði geothermal power plant in after the year 2010. Information specified by the power producers was used and therefore installed capacities for the simulation year 2010 includes more recently updated values. In Iceland, 13 hydro power plants produced 96% of the total electricity generation in 2010. The remaining 4% were supplied by numerous small-scale hydro units that do not feed electricity directly into the main grid but directly into the distribution grid (see Figure 17). These small units are aggregated into one unit so that the capacity in the simulations would be 1883MW as shown in table 2-5.

6-1: Installed capacities used in the BALMOREL model

Installed Capacities	Power capacity (MW_{el})	Heat Capacity (MW_{th})	Reference
Geothermal Power plants			
Bjarnarflag	3.2	0	[52]
Hellisheiði	303	130	[33]
Húsavík	1,7	0	[53]
Krafla	60	0	[37]
Nesjavellir	120	300	[36]
Reykjanes	100	0	[54]
Svartsengi	75	150	[32]
Total Geothermal Capacities	**662.9**	**580.0**	
Hydro Power Plants			
Andakíll	8.2	-	[48]
Blanda	150	-	[39]
Búrfell	270	-	[40]
Hrauneyjar	210	-	[42]
Írafoss	48	-	[45]
Kárahnjúkar	690	-	[41]
Lagarfoss	7,5	-	[50]
Laxá	27,5	-	[43]
Ljósifoss	15	-	[45]
Mjólká	8,1	-	[49]
Sigalda	150	-	[44]
Steingrímsstöð	27	-	[45]
Sultartangi	120	-	[46]
Vatnsfell	90	-	[47]
Small Scale Units (aggregated)	61.7	-	
Total Hydro Capacities	**1883**	-	[10]

6-2: Allowed investments for the BALMOREL model for the years in the simulation

	New Power Plants to Invest in	Power Capacity	Heat Capacity
2010	No new investments	-	-
2020	Geothermal unit 1	Model suggests capacity	no suggested capacity
2050	Geothermal unit 2	Model suggests capacity	no suggested capacity

Table 6-2 shows the power plants that BALMOREL is allowed to invest in for the years 2020 and 2050. The model is only allowed to invest in one geothermal unit for the year 2020 and another geothermal unit for the year 2050. The model will itself decide the capacity that needs to be invested in based on the demand for each year.

In the BALMOREL model created for Iceland, heat is only produced for the base year and the assumption is made that the need for new investments in heat capacities is less than the need for investments in new power capacity. Large amounts of heat are wasted in the geothermal power plants as can be seen in Figure 9 and this waste heat is assumed to be available for the production of district heat without the need for investment optimization. Increased demand for heat can be met by either turning some of the geothermal power plants into CHP plants or by retrofitting of existing heat production units that utilize geothermal heat. Minimizing the heat losses in each geothermal power plant in Iceland is an interesting topic but is not a subject of this study[24].

Transmission losses are assumed to be 3.74% of the total electricity production for all scenarios and for all years. These losses include losses both in the main grid and in the distribution grid in Iceland and are the losses forecasted by the National Energy Authority of Iceland (NEA) for the year 2050. The Losses for the years 2010, 2020 and 2050, as forecasted by NEA, are summarized in Table 6-3 for comparison [12]. It can be seen that the losses for the year 2010 were 2.84% and thus somewhat lower than for the year 2050 and what is used in the BALMOREL simulations. In reality, the transmission losses are furthermore dependent on the load on the grid at each time and the voltage of the transmission line. Ideally, variable losses would be used as input for BALMOREL but the model does not facilitate the specification of losses for every year in the simulation nor load dependent losses. This could have been modified but was considered unnecessary for the purpose of this study. By assuming the losses of 3.74%, the simulated electricity generation will be slightly overestimated for the years 2010 and 2020 for the base-case scenario. For the other scenarios, introduction of increased demand by energy intensive industries and the transmission cable could lead to a decrease in these losses (percentage wise) if the electricity is delivered from the transmission grid rather than the distribution grid. This discussion will not be elaborated on here.

Table 6-3: Losses in the transmission grid as forecasted by NEA of Iceland (adopted from [12])

Year	Losses distribution grid (GWh)	Losses main grid (GWh)	Total production (GWh)	Losses (%)
2010	155	330	17059	2.84%
2020	196	408	18973	3.18%
2050	310	495	21514	**3.74%**

For the scenarios “cable” and “cable and industry” new connections were established in the input files to BALMOREL. These connections can be seen in Figure 31 below. As discussed in section 6.2.1 a new region for the energy intensive industries was created. This new region has its own electricity

[24] This can be done by use of tools like exergy analysis where the use of process heat can be optimized.

demand and electricity is supplied from the “Iceland Region” in the figure. The region for energy intensive industries therefore receives electricity from “Iceland Region” through the transmission cable which from before was assumed to have a power capacity of 500MW. The losses in this transmission cable are zero but since electricity production is done in “Iceland Region”, grid losses of 3.74% are accounted for.

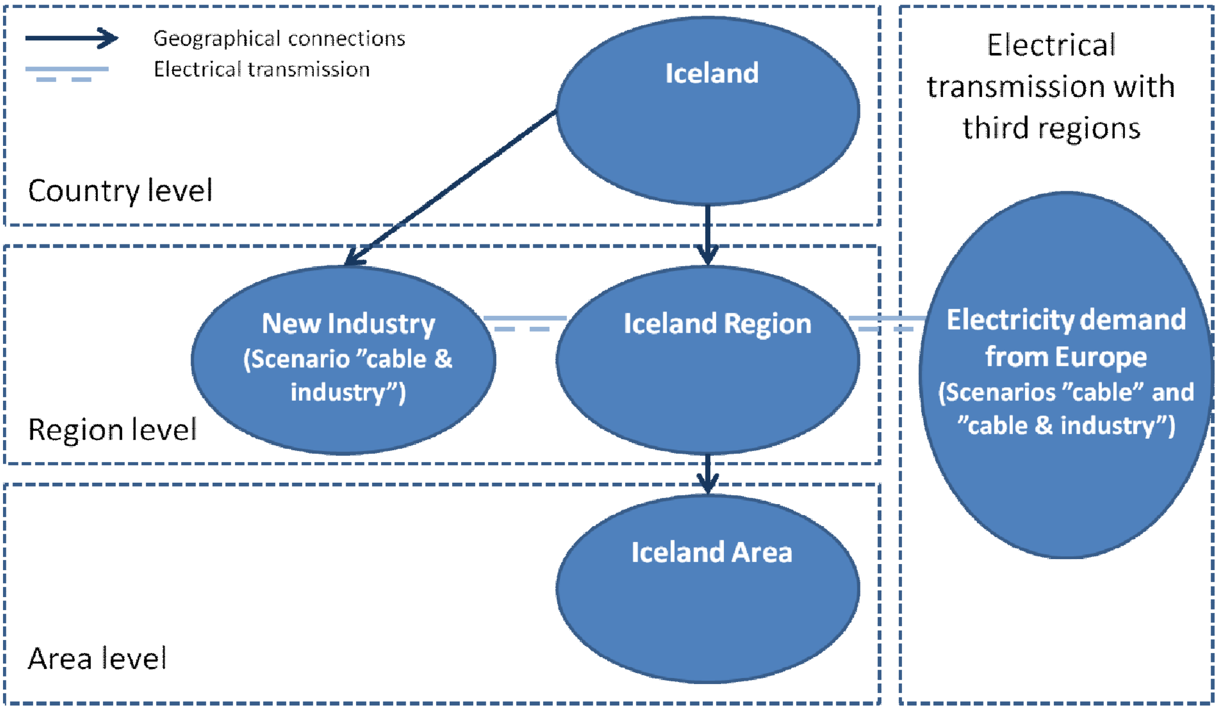


Figure 31: Electrical transmission connections for Iceland as modelled in BALMOREL

The transmission cable to Europe that is used in the scenarios “Cable” and “Cable and Industry” is in the BALMOREL model connected to the region “Iceland Region” as shown in Figure 31. This transmission cable is, unlike other transmission cables in the model, modelled as a new electricity demand only and is not connected to a geographically specified region. The reason for this approach is that the connection is intended to simulate connection between Iceland and the UK and the UK has not been modelled in BALMOREL yet. The UK power system is instead represented by a (hourly) spot market price profile from the year 2010 which is an alternative approach to modelling the whole energy system in UK. A pre-made feature of the BALMOREL model is utilized for this purpose. The transmission cable to between Iceland and UK is assumed to have no losses. This is obviously a simplification for a 1200 km long transmission cable but it can minimize the risk of overestimating the energy production needed for this cable. When more detailed information on the losses from this transmission cable is available, this can be implemented to the BALMOREL model.

6.2.5. Technology Characteristics

The power plants are divided into either geothermal units or hydro units and the technology characteristics that are used in the BALMOREL model can be seen in table 6-4 below. Hydro power plants are all assumed to have a water reservoir and one reservoir is assumed to serve all hydro power plants. The fuel efficiency for hydro power plants is assumed to be 100% and the lifetime is assumed to be 60 years. The geothermal units are of two types; CHP units and condensing units. The condensing units produce only electricity while CHP plants produce both electricity and heat. Both these types are assumed to convert geothermal heat into electricity with an efficiency of 12% which is consistent with the efficiencies in the year 2010 and shown in Figure 9. The full load hours for the geothermal power plants is fixed at 7765 hours per year which are the observed full-load hours for the year 2010 as shown in 6-4. The lifetime of geothermal power plants is assumed to be 40 years. These technology characteristics are the same for all scenarios and years in the simulation. New geothermal units are assumed to be condensing and have the same attributes as shown in table 6-4. Fuel efficiencies are not assumed to decrease with years of operation.

6-4: Technology characteristics for power producing units in the BALMOREL simulation.

Technology Characteristics	Technology Type	Fuel Efficiencies *(%)*	Full Load Hours *(hours/year)*	Lifetime *(years)*
Hydro power plants	Water reservoir	100%	Model decides	60
Geothermal power plants	Condensing	12%	7765	40
	CHP	12%	7765	40

6.2.6. Fuel Characteristics

The technologies described in previous section utilize either geothermal heat or water as the source for energy. For the purpose of this study, geothermal heat was added to the BALMOREL model. Before the modifications, BALMOREL allowed for various types of fuels to be utilized but geothermal heat had not been included. Due to the nature of the resource, the decision was made to divide the geothermal heat further into high- and low-temperature geothermal heat. Power producing geothermal units located in high temperature geothermal fields can then utilize high-temperature geothermal heat while geothermal units that are located on low temperature geothermal fields can utilize the low-temperature geothermal heat. This distinction can be useful later on even though only power producing geothermal units are analysed in this study.

No gas emissions are assumed to be from the use of geothermal heat in geothermal power plants but in reality, these power plants emit both Carbon dioxide (CO_2) and Hydrogen sulphide (H_2S) to a certain extent.

There are no fuel restrictions set in the model and the fuel potentials are assumed infinite for both geothermal heat and for water (confirm). In BALMOREL, both the resource limits and generation limits can be specified for each fuel in the simulation. The generation of electricity from geothermal and hydro resources is unlimited in this study, which means that the electricity demand can be met at all times by introducing new power capacity when needed. Information on the seasonal inflow of water to the hydro reservoirs in Iceland could not be obtained in this study and an inflow variation profile for Norway was used instead. This profile is different from the Icelandic profile but the inflow is large enough in order not to restrict the generation of electricity from hydro power plants. The generation of electricity from hydro resources is therefore only limited by the installed power capacities of existing hydro power plants.

6.3. Model Criteria and Objective

For this study, BALMOREL version 3.02 (from September 2011) was used and adjusted to meet the purpose of this study. Geothermal power plants have not been modelled yet in BALMOREL and are therefore added to the model for this study. In this section, a discussion on how this was accomplished is made along with a discussion on how the BALMOREL model seeks to minimize system costs based on a set of constraints. These constraints are equations that ensure the correct functionality of the model and set the boundaries for the problem solving.

The geothermal units operate on a relatively stable electrical output while hydro units are used in a more flexible way and are used in response of varying electrical demand. A schematic way of how these two types of power plants are modelled in the BALMOREL model can be seen in Figure 32 below. All hydro power plants are assumed to utilize one reservoir while each of the geothermal power plants has separate consumption of geothermal heat. The model is constrained to the installed power capacities and also to the inflow of water to the reservoir. There are no limitations on the geothermal heat used for electricity production (nor the heat production).

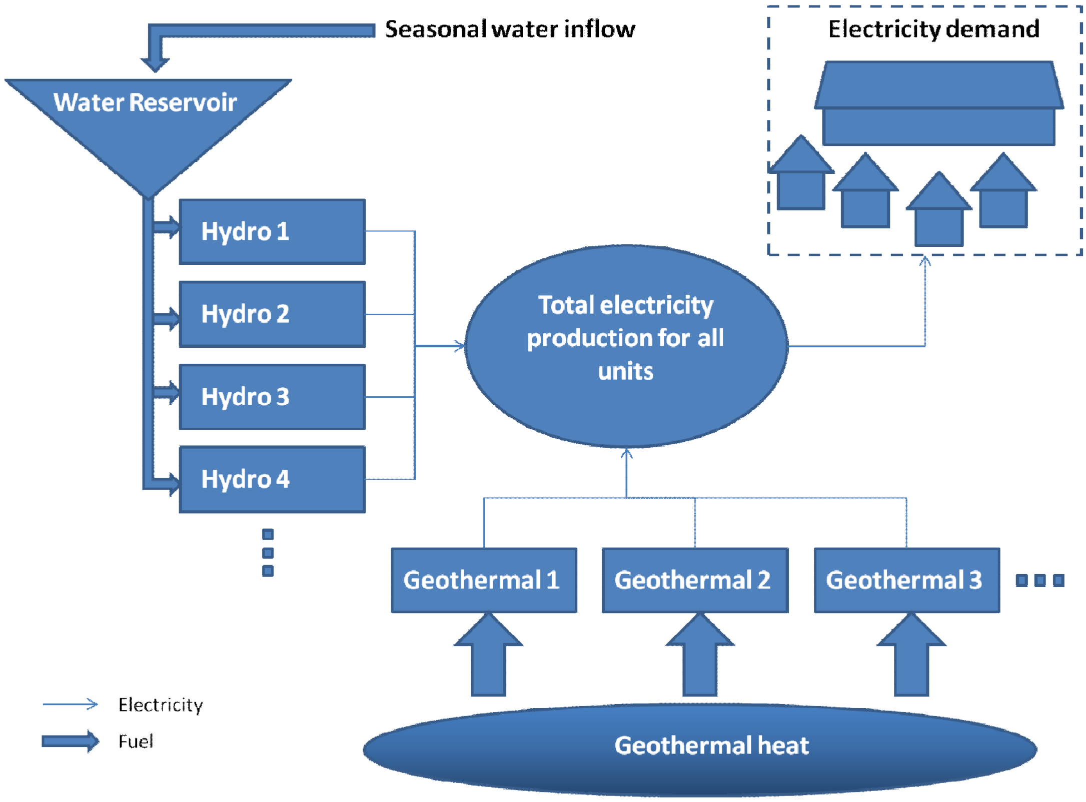


Figure 32: Schematic representation of the electricity production in BALMOREL.

The objective of the BALMOREL is to minimize the costs from operating the whole energy system on annual basis. In order to get the lowest costs for the system, the model decides the electricity production from each power plant at every hour of the year. In principle, the model allows the units with the lowest short-term marginal costs to produce more than units with higher short-term marginal costs. The short term marginal costs are costs that are dependent on the electricity production every hour and are dependent on the operation costs for each power plant. In a system with a competitive energy market, this principle is valid at all times and the cheaper units are in operation longer than the more expensive ones (assuming no down-time of the cheaper units). In Iceland however, this principle is not valid since there is no real energy market in Iceland but only a regulation market for system balancing and operated by the transmission system operator Landsnet.

The geothermal units were modelled as *non-dispatchable* units, meaning that the power generation cannot be adjusted or dispatched according to needs. Instead, the generation is fixed to a variation profile that describes the hourly variations in the generation for a whole year. For this study, the variation profile is assumed constant and therefore the electricity generation from geothermal units is fixed. The full load hours for geothermal power plants is assumed to be 7765 hours as shown in table 6-4 and applies to both existing and new geothermal units. **The electricity generation from geothermal units is therefore fixed for every hour of the year** and the power generation is found as:

$$Plant\ power\ capacity\ [MW] \cdot \frac{Specified\ full\ load\ hours\ [h]}{Maximum\ full\ load\ hours\ [h]}$$

Thus for example for the geothermal power plant Nesjavellir (120MW_el), the power production is:

$$120\ [MW] \cdot \frac{7765\ [h]}{8760\ [h]} = 106.4\ MW$$

The geothermal power plants are therefore not producing at maximum power capacity over the year. This can be interpreted in a way that the *availability* of the geothermal power plants is less than 100%. The availability of a power plant is the percentage to which the power plant is in utilization for a given year and is in the equation above or around 90%. All geothermal units in the simulation are assumed to have this availability factor (since they all have the same full load hours). For the remaining 10%, the power plant is assumed to be out of operation due to maintenance or technical failure. With 7 geothermal power plants in Iceland, the absence of one unit is expected to have greater influence on the total generation from geothermal units than if there were more power plants. Especially the influence on the total generation becomes apparent when a large power plant is out of operation due to maintenance. This is contrary to the availability of hydro power plants where absence of one power plant is less likely to influence the total generation from hydro units since there are 15 power plants in the model. The availability for hydro units is assumed to be 98% and therefore higher than the availability of the geothermal power plants. The way that this availability for hydro units is included in BALMOREL is different from geothermal availability in the way that the maximum production every hour is reduced to 98% of the installed capacity.

As discussed in section 2.3, the hydro power plants are in Iceland used to meet the peak demand; they are therefore in a way more flexible than the geothermal power plants and have also a faster response time. The **electricity generation from hydro power plants is not fixed at every instant** (every hour) and they are therefore used to meet the peak demand at every hour which then again is defined by the variation profile for the electricity demand. The hydro power plants therefore obtain the same generation profile as the electricity demand (discussed in section 6.2.3) and the generation profile is therefore fixed for all the years in the simulation. The total annual electricity generation is however not fixed and depends on the investments made in new geothermal units.

7. Model Results

In this section, the results from the model simulations done in BALMOREL model created for Iceland are presented and analysed. Firstly the model simulations for the base year are compared with real values for the year 2010 to see if the model can be considered to represent the Icelandic system sufficiently well. The electrical generation for the scenarios discussed in section 5.1 (and shown in Figure 27) is then discussed and compared to the resource limits laid out by the master plan for hydro and geothermal resources as discussed in section 3 and shown in table 3-2. A discussion on the issue of connecting two different energy markets is laid out and is followed by a result summary.

7.1. Model Validation

In order to get an idea of how the model simulates real conditions, the electricity generation from the simulation in the year 2010 was compared to observed values for the same year. The electricity generation from the simulation can be seen in Figure 33 and the observed generation is shown in Figure 34. In both cases, geothermal power plants operate as base load plants while hydro power plants are used to meet the peak load. The total simulated generation is slightly higher at every hour of the year than the observed generation. The reason for that is that the simulation assumes higher grid losses than what was the reality in 2010, requiring power plants to produce more electricity in order to meet the same demand. The peak power in 2010 was 2211MW in the simulation and was 2090MW in reality.

The geothermal power production is constant in the simulation for all hours and the total generation from all units is 588 MW. This is a somewhat higher production than was observed in 2010 and is due to the fact that the installed capacities were lower in 2010 than what is defined in the model (575MW in reality in the year 2010 as oppose to 662MW in the model). Geothermal power plants follow a constant profile with the installed capacities determined by the full-load hours and it would therefore have been an option to modify the full-load hours of the geothermal units in the simulation in such a way that the production is the same as was observed in the year 2010. However, the required work for having different full load hours for different years and specified for each power plant is left as a task for further development of the model. For the purpose of this work, the full load hours are assumed to be 7765 hours which is consistent with what the national energy association has published and can be seen in 2-5. As it is modelled in BALMOREL, the full load hours are used to control the generation from the non-dispatchable generation units like the geothermal power plants and can thus be looked at as also as the *availability* of the units due to maintenance or technical failure. Since there are only a few geothermal power plants operating in Iceland, the absence of one power plant in the system has significant impact on the total production from all geothermal plants. This effect can be seen in Figure 34 in the summertime when Hellisheiði geothermal power plant was out of operation.

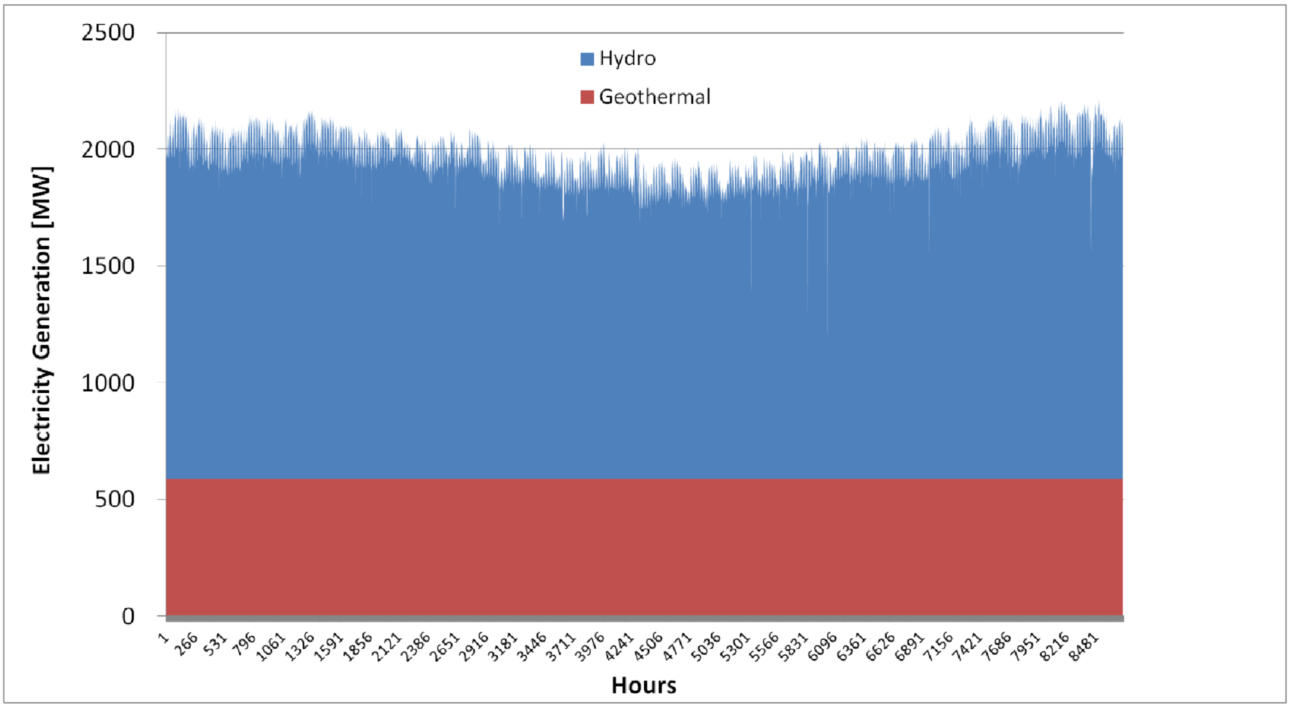


Figure 33: Electricity generation in the year 2010 as simulated by BALMOREL.

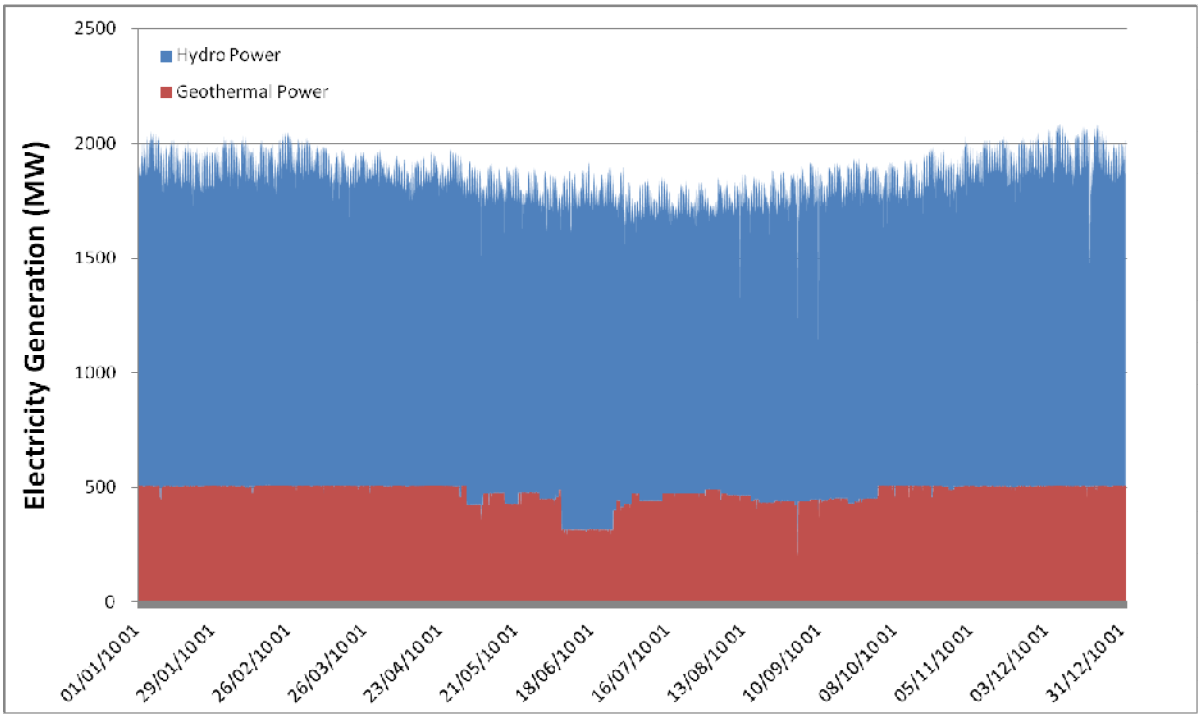


Figure 34: The real production delivered to the main grid in 2010 [18]

A comparison between the total production of electricity for the simulation and for the observed values can be seen in Figure 35 below. The figure shows that the total generation from hydro units is slightly underestimated in the simulation while the generation from geothermal units is overestimated. The difference is summarized in table 7-1. The production from the geothermal units is overestimated due to above mentioned reasons of the installed capacities and the full-load hours. The hydro units operate as marginal units and therefore supplying the rest of the needed electricity demand. The difference between the total production as simulated by the model and as observed is less than 1% which is considered negligible. This is a consequence of the grid losses being assumed constant while in reality, they depend on the electricity load at every instant and are thus variable.

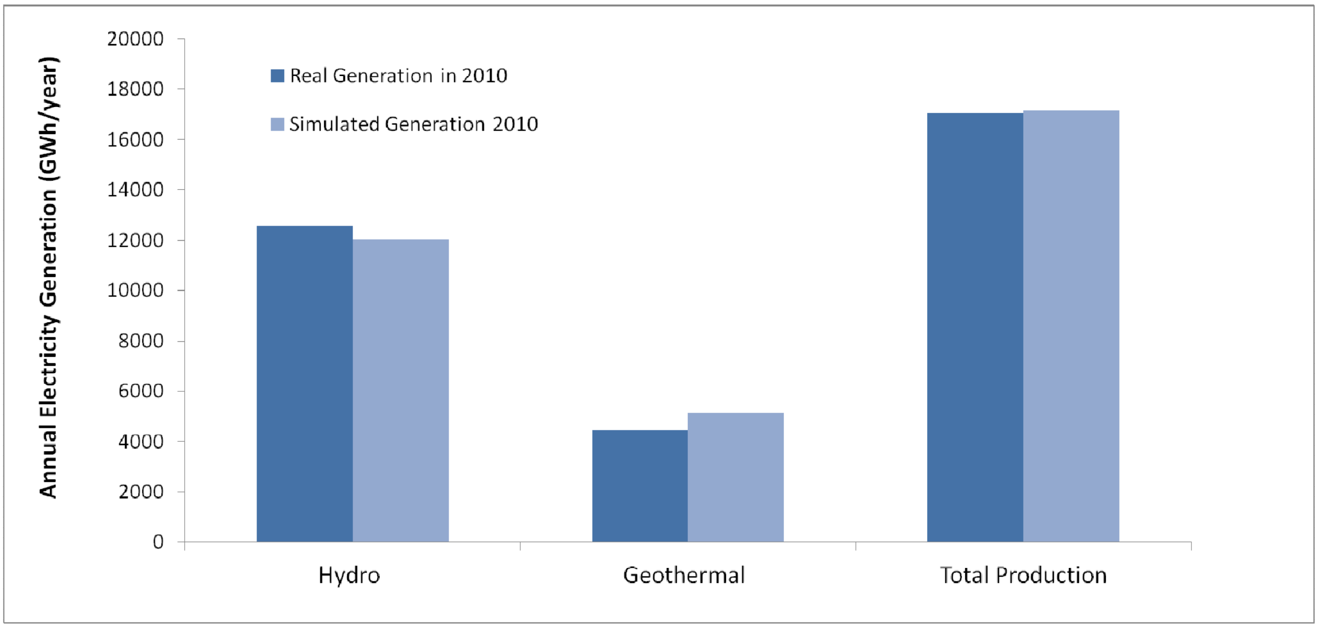


Figure 35: Annual electricity generation in 2010; a comparison between simulated and observed values.

7-1: Comparison of the total electricity generation in the simulation and observed generation in the year 2010.

	Simulated Generation 2010 *GWh/Year*	Real Generation in 2010 *GWh/year*	Difference *%*
Hydro	12037	12592	4%
Geothermal	5133	4465	15%
Total Production	17171	17059	0,7%

Based on this discussion, the model is considered to resemble the Icelandic electricity system sufficiently for the base year 2010. All three scenarios that are under discussion in this project will be based on this model.

7.2. “Base-Case” Simulation Results

The electricity generation for the simulated years of 2010, 2020 and 2050 is shown in Figure 33 below. As shown in table 6-2, the model is only allowed to invest in a (condensing) geothermal power plant and therefore does not suggest investment in hydro power plants. The model suggests investments in a geothermal power plant in the year 2020 with a power capacity of around 20MW and suggests also an investment in another geothermal power plant in the year 2050 with a power capacity of around 350MW. In reality, some of these investments can be avoided by utilizing more of the hydro power capacity that is already installed (see discussion in section 2.3). This unused hydro capacity was around 4000GWh in the year 2010 and by assuming that there are no restrictions on the electricity generation from hydro power plants (i.e. assuming that the water inflow to the reservoirs is sufficient), investments of around 450MW could be avoided. In practice, the suggested investments made by the BALMOREL model could therefore prove unnecessary since unused hydro capacity could be used to meet the increased demand until the year 2050 (as predicted by the National Energy Authority of Iceland).

The reason for the model not suggesting increased electricity generation (higher utilization) of the hydro power plants is the restrictions set by the balance equations of the model. The variation profile for hydro power plants is *not fixed* in the BALMOREL model but is determined by the demand profile for electricity demand as discussed in section 6.2.3. This is also a result from the fact that geothermal power plants are modelled as to have a fixed electricity generation profile for the whole year and are thus not as flexible as the hydro power plants. The electricity generation for the hydro power plants is also limited by the power capacity of the hydro power plants and by the inflow of water to the reservoirs. The suggested investments made by the BALMOREL model does account for these limitations and investments in new geothermal power plants is determined such that the peak demand can be met each year with the existing hydro power capacity.

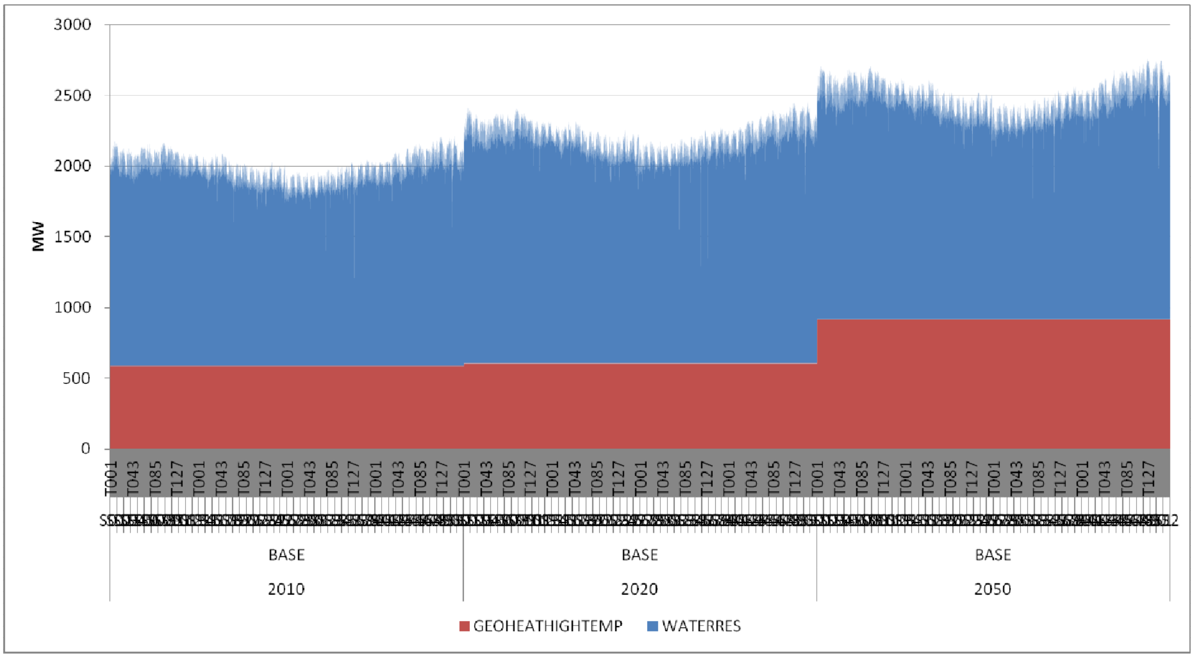


Figure 36: Electricity generation as simulated by BALMOREL for the case „Base-Case“. Power plants using (high-temperature) geothermal heat is shown in red and power plants that use water (from the hydro reservoir) are shown in blue.

7.3. "Cable" Simulation results

The results from the BALMOREL simulations for the scenario "Cable" is divided into two parts; fixed and flexible electricity generation (discussed in section 5.1). The annual electricity generation is the same for both of the fixed and the flexible scenarios and the annual demand is 5.95TWh as discussed in section 6.2.3.

7.3.1. Fixed Electricity Generation

The electricity generation for the simulation years 2010, 2020 and 2050 is shown in Figure 37 below. With the introduction of the transmission cable to Europe in the year 2020, investments in new geothermal units is suggested for the year 2020 and for the year 2050. In the year 2020, an investment in a power capacity of around 750MW is suggested while for the year 2050, a capacity of 350MW is suggested. Thus for a transmission cable with a power capacity of 700MW, an investment in geothermal power plant with a higher power capacity is needed. The need of a higher power capacity than 700MW is because the model accounts for the availability of the new geothermal power plants which is less than 100% (as discussed in section 6.3). Since hydro power plants have only around 450MW of unused power, an investment in new power capacity is unavoidable for this scenario since existing power capacity in Iceland (for the year 2010) is not sufficient.

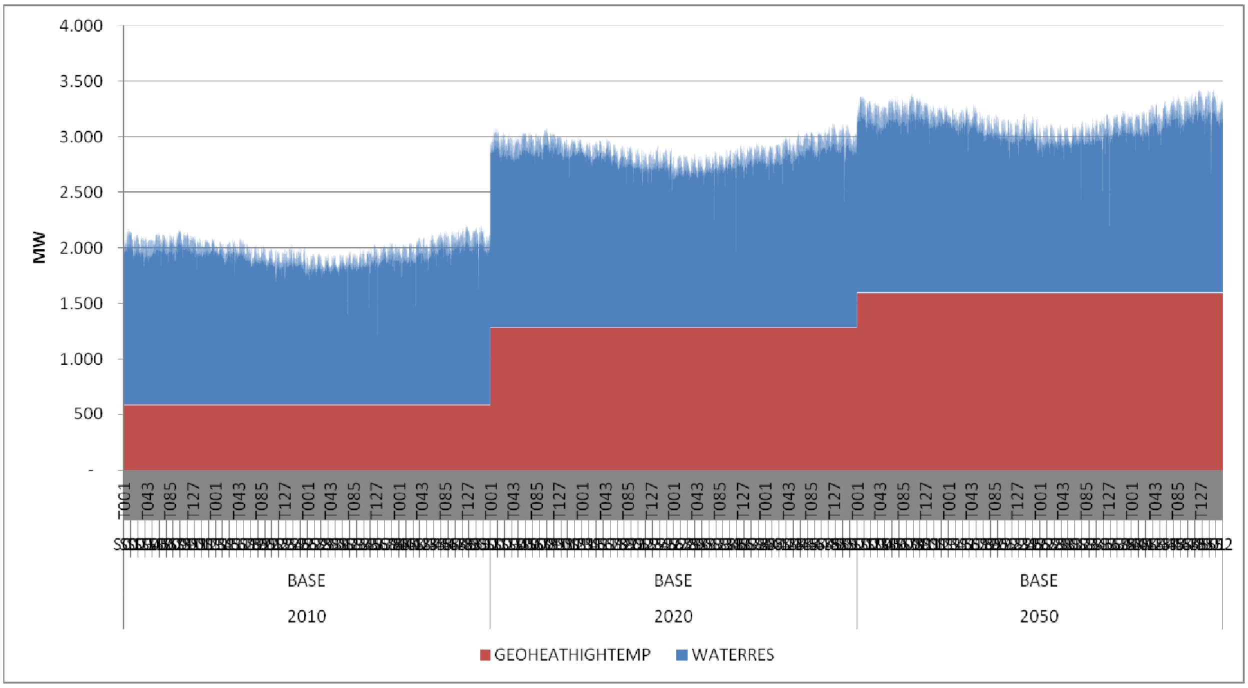


Figure 37: Simulated electricity generation for the scenario „cable" for the years 2010, 2020 and 2050. Power plants using (high-temperature) geothermal heat is shown in red and power plants that use water (from a water reservoir) is shown in blue.

The total electricity generation for geothermal and hydro power plants in the simulated years is shown in tables 15-2 and 15-3 and it can be seen that the electricity generation increases for both types of technologies until the year 2050. The full-load hours for the hydro and geothermal power plants is also shown in these tables. The full load hours for hydro power plants varies between years in order to compensate for the forced export due to the transmission cable but the model does not suggest higher utilization of the hydro power plants than 7300 full load hours per year. The unused hydro capacity in the simulation years is shown in table 7-2.

7-2: Simulation results for hydro power plants.

Hydro Year	Electricity Generation *GWh*	Installed Capacity *MW*	Full-load hours *h*	Unused Hydro *GWh*
2010	12037	1883	6393	4458
2020	13746	1883	7300	2749
2050	13443	1883	7139	3052

7-3: Simulation results for geothermal power plants

Geothermal Year	Electricity Generation *GWh*	Installed Capacity *MW*	Full-load hours *h*
2010	5133	662	7754
2020	11220	1447	7754
2050	13950	1799	7754

7.3.2. Flexible electricity generation based on a market profile

In this scenario, the electricity generation for the transmission cable is assumed to be flexible and the generation is dependent on the electricity price at each hour. Electricity is exported when the marginal costs of the Icelandic power plants are lower than they are for the power plants in UK. Electricity imports through the transmission cable are set to zero in the BALMOREL model and are thus not allowed. A spot market price profile for the year 2010 in UK was implemented to the BALMOREL model and it determines the electricity generation from Icelandic power plants at every hour in the simulation years. With a lack of accessible data for the operating costs of Icelandic power plants, a discussion on the actual amount of exported electricity is hard to determine at this point and is therefore not laid out here. More detailed data on the costs of the Icelandic power plants is therefore necessary and this can be implemented in future versions of the BALMOREL model created in this study.

As discussed in section 3, the power prices in Iceland are expected to be lower than in the UK and this was assumed to be the case in the simulations. Figure 38 shows the results from these simulations for a random week of the year 2010. Electricity generation is, as expected, constant throughout the whole year and the electricity generation is 5.95TWh/year as for the scenario with fixed electricity generation discussed in section 7.3.1. The transmission cable is used to its full capacity all year around.

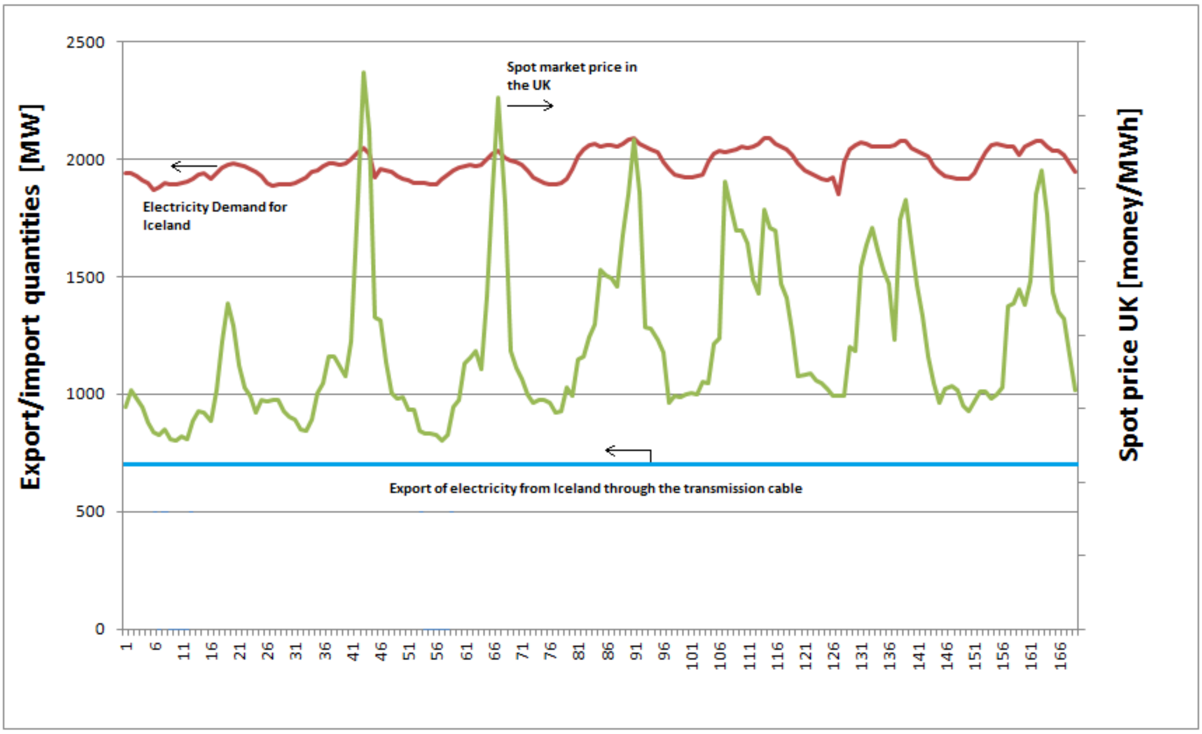


Figure 38: Results from BALMOREL simulations with price dependent electricity generation. A spot market price profile for the year 2010 was used to resemble the UK energy system.

With a higher power price in Iceland than in the UK, the results are different and electricity is exported only when prices in UK are higher than they are in Iceland. A discussion on some of the issues related to the connection of the Icelandic and the UK energy markets is done in section 8.

7.4. "Cable and Industry" Simulation Results

In this scenario, both the transmission cable to Europe (with a power demand of 700MW) and an energy intensive industry (with a power demand of 500MW) are included in the simulations. The electricity generation for the simulated years can be seen in Figure 39 below. The model suggests an investment in a geothermal power plant of around 1300MW in the year 2050 and of around 350MW for the year 2050. Unused hydro capacity could, as for the other scenarios, reduce the need for investments in new power capacity of around 450MW. Thus by introducing both a transmission cable to Europe and the energy intensive industry into the Icelandic energy system before the year 2020, investments in new power capacity are required. The power capacity needed for this increased demand is in the range of around 800-1300MW and is an increase of around 30-50% from the year 2010. This is a significant change to the existing power system and reflects again the fact that the Icelandic system is small compared to projects of this magnitude.

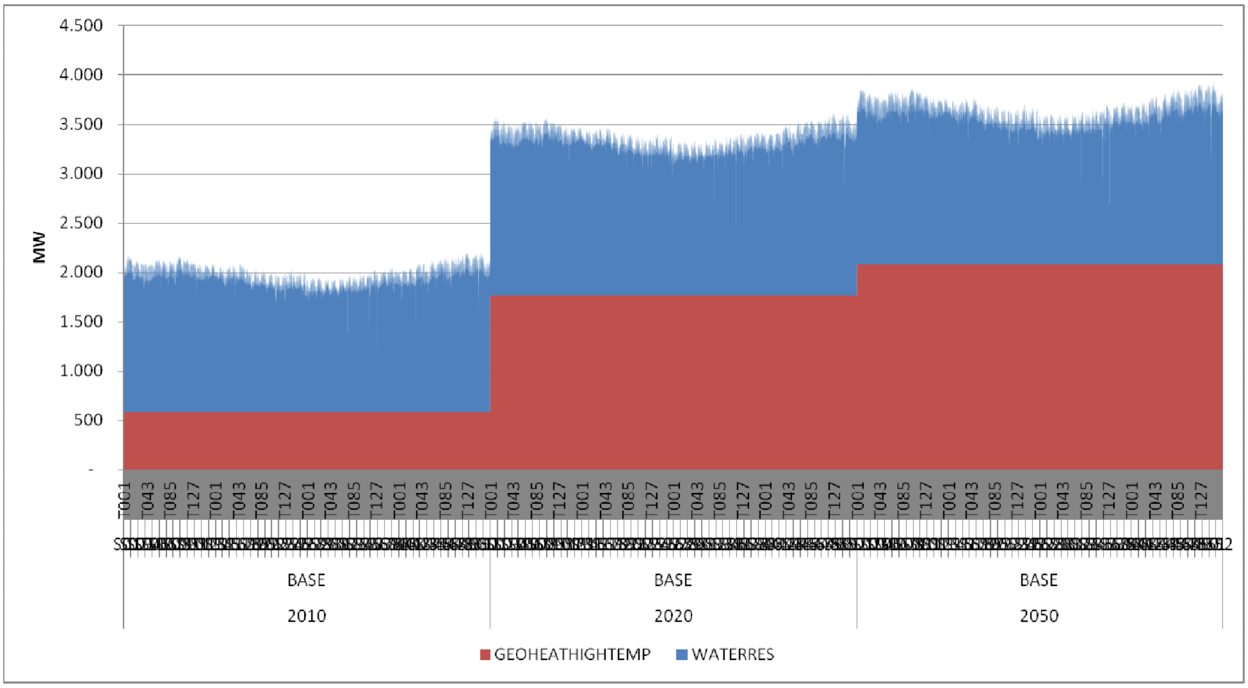


Figure 39: Electricity generation for the case „Cable and Industry". Power plants using (high-temperature) geothermal heat is shown in red and power plants that use water (from a water reservoir) is shown in blue.

7.1. Resource Limits

The results from previous sections (7.2, 7.3 and 7.4) show that investment in new capacity is needed for each of the three scenarios as a consequence of increased annual demand for electricity. Figure 40 shows the total annual electricity generation for each of the three scenarios created in this study and compares the generation to the limits specified in the master plan for hydro and geothermal resources as discussed in section 3 (and shown in table 3-3). The figure shows that generation limits are exceeded in the year 2050 for the scenario "cable and industry" while the limits are not exceeded for other scenarios and other years. The electricity generation for the scenario "cable and industry" is 31.6 TWh/year while the limits are 30.1 TWh/year as laid out by the master plan for hydro and geothermal resources. This is of great concern since power plant options that are on the *waiting list* in the master plan would be utilized. Other energy resources than water and geothermal heat will have to be exploited for this to be avoided. It can be reminded that the total projects evaluated in the second phase of the master plan covered options with a possible electricity generation of 47.5TWh (as shown in table 3-2), thus making the scenario "cable and industry" a technically feasible option but only at high environmental costs.

What is also important here is that the resource limits shown in table 3-2 assumes that each geothermal resource is utilized for 50 year while more than a 100 years of utilization is considered to be a sustainable utilization as discussed in section 4. It could therefore be argued that the resource limits could be exceeded earlier than by the year 2050. With the maximum electricity generation from geothermal resources in Iceland being around 14 TWh (as shown table 3-2), a rough estimation means that only 7 TWh of this can be used if the resources are to be used in a sustainable way. This means that the available electricity generation drops from 30TWh/year to around 23TWh/year and the resource limits could therefore be exceeded earlier and for both the scenarios "cable" and "cable and industry".

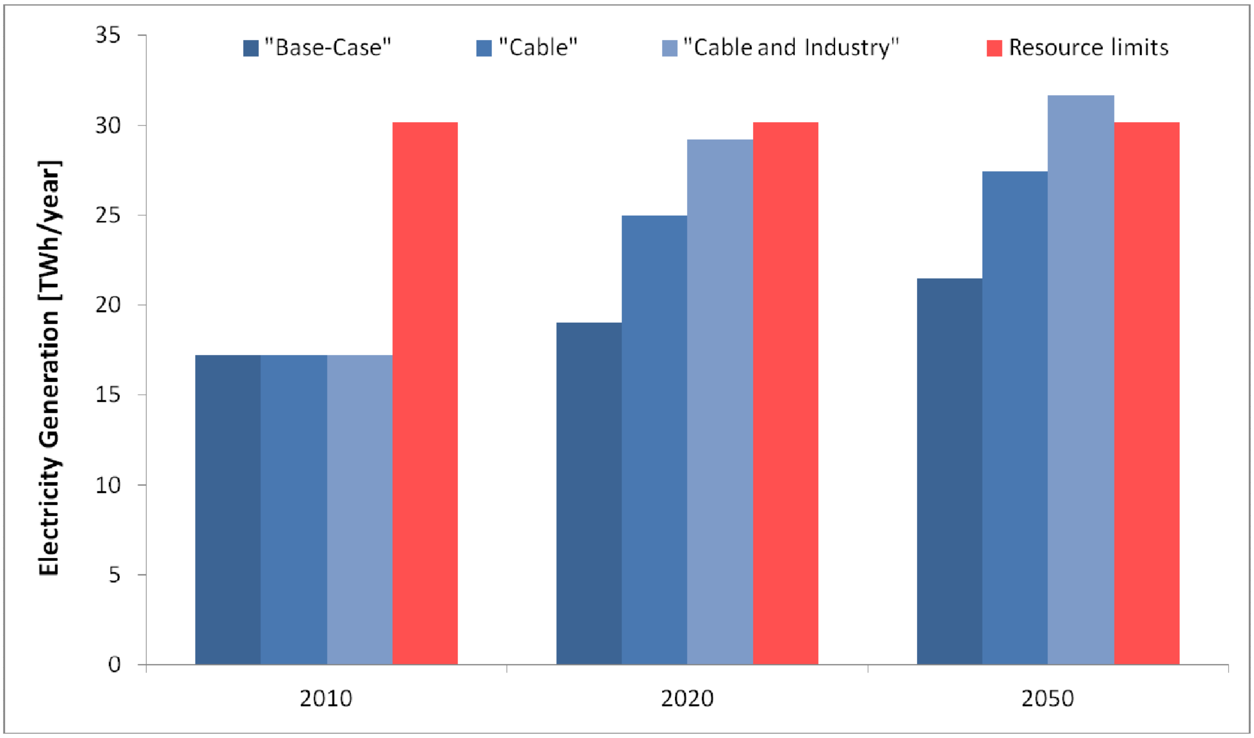


Figure 40: Electricity generation for the simulated scenarios compared with the resource limits as specified in the Icelandic master plan for hydro end geothermal resources.

8. Discussion

In this study, an overview of the Icelandic energy system was presented and its development in the next decades was analysed by using the concept of energy scenarios. The energy system was implemented in the energy analysis tool BALMOREL and the energy scenarios created in the study were simulated and analysed. The use of the BALMOREL model proved to be a useful tool for the analysis and some of the problems that could occur in the coming decades were revealed. In this section, a review of the previous sections is done and the tools used in the study are further discussed and evaluated. Whether these tools proved useful in the analysis and how is addressed.

As discussed in section 3, the Icelandic energy systems can experience large changes in the coming years with the introduction of new energy intensive industries and with a transmission cable to Europe. The governmental plans and policies in Iceland set the limit of such expansion based on sustainable development. The master plan for hydro and geothermal resources is an important part of this development and can ensure that new power plants built in Iceland have less negative impacts on the environment and the society. From Figure 40 it can be seen that power plants that are on the waiting list of the master plan will have to be utilized in order to meet the increasing demand. The simulations are preliminary but can give a good indication of the future development and there is a certain risk that most of the hydro and geothermal heat resources will be fully exploited in coming years, thus requiring other resources to be utilized for electricity production. As discussed in section 3, the grouping of proposed projects in the master plan into categories (see Figure 21 for categories) is not finite and discussion on this matter is ongoing in the parliament. This fact makes it difficult to conclude on whether or not the resource limits will be exceeded in near future or not. It is however clear that excessive electricity production from these resources can have large impacts and a careful management of these resources is therefore essential. The discussion on the sustainable use of renewable resources is very important in this respect and was discussed in section 4.

From Figure 9 it can be seen that large amounts of heat is wasted when geothermal heat is used for electricity production. This raises the question whether this heat can be utilized more efficiently and whether using it for electricity production is indeed a feasible option compared to using the heat directly for other purposes. Since district heating is already met by using geothermal heat, this waste heat can be used in various manufacturing processes that can be situated by/nearby the geothermal power plants.

The issue of connecting the Icelandic and UK energy markets involves aspects that could not be covered in this study. The two energy markets are different and the influence the connection can have different effects depending on the type of contract made between the two countries. In this study, two types of contracts were simulated (see section 7.3); First type of contract involves that UK buys a fixed amount of electricity at a given price and second type of contract involves linking the Icelandic market to the UK market. The difference between those contracts is that electricity generation for the first type is fixed while it varies for the second type of contract depending on the difference in short-term marginal costs for the Icelandic and the UK power units. The costs for Icelandic power units could not be attained for this study, making this type of contract difficult to analyse. With the assumption that the costs are always lower than in the UK, the electricity generation is constant and the transmission cable is fully utilized (as can be seen in Figure 38). With higher costs in Iceland than in the UK, it could turn prove beneficial for Iceland to *import* electricity from the UK. In the UK, more use of renewable energies in the power production is expected in near future which raises the question of how cost-competitive the Icelandic power production is to energy production from other energy conversion technologies such as wind turbines (on- and offshore).

The connection of Iceland to the UK energy market has several complications and one of them is that consumer prices in Iceland will be higher. The increase could be large since the difference between the Icelandic and UK electricity prices is high at present. If the national power company in Iceland will be a member of the UK power market, the national power company will earn revenues at the expense of the Icelandic population. This increased expense can be avoided somewhat by appropriate regulations made by the government but these matters need to be discussed thoroughly.

For this study, energy scenarios were used as a tool for analysing the future development of the Icelandic energy system. These scenarios are explorative scenarios and were created based on the future options/trends that Iceland is facing at present. This type of scenarios can give a good idea of what the future might bring and are considered to be good alternative to the predictive scenarios laid out by the National Energy Authority of Iceland. The advantage of using energy scenarios that are either explorative or anticipative (see Figure 25) is especially high since the predictive scenarios made in Iceland do not account for energy intensive industries or other unpredictable projects.

As discussed in the introduction of this study (section 1), the STREAM model was used to get an overview of the Icelandic energy system and to collect some of the data necessary for further simulations in the BALMOREL model. The STREAM model served its purpose as to give a good overview of the Icelandic energy system as a whole but the method of using the STREAM model as a way to collect data for the BALMOREL model did not prove to be a good approach. This is because these two models have their own complexities and functionalities that are not comparable. The models are furthermore developed in different software with no possible interchange of data files or result files. Establishing such connections may not prove beneficial either since the complexities of the two models is high enough already.

When using the BALMOREL model as an analysis tool, large amounts of data is needed as input to the model and large amounts of data can be extracted at the end of the simulations. This data can be more easily managed by use of Microsoft Access and developers of the BALMOREL model have already made several options in that regard. This includes BALMOREL input database (BID), BALMOREL results database (BRET) and BALMOREL user interface (BUI). Like for the BALMOREL model itself, these options can be adjusted and changed according to the user needs. Data handling is considered to be of great importance when BALMOREL model can greatly facilitate its use. Using the BALMOREL as a tool for the analysis proved useful and by implementing Iceland into the model, as was done in this study; more analyses can be performed in near future. The BALMOREL model of Iceland created in this study needs further development and some suggestions for improvements of the model and project proposals is discussed in section **Error! Reference source not found.**.

9. Conclusion

In this study, the Icelandic energy system was presented and its development in the next decades was analysed by using the concept of energy scenarios. With an abundance of powerful glacial rivers and geothermal heat, Iceland can supply most of the energy demand by local renewable resources. Electricity is produced by hydro- and geothermal power plants and more than 99% of the electricity generated in the year 2010 was generated with these technologies. The total electricity generation in that same year was 17TWh of which hydro power plants produced 74% and geothermal power plants 26%. The generation of electricity from other types of energy resources than water and geothermal heat is less than 0.1%, making the electricity production almost entirely based on renewable resources. Most of this electricity is consumed by energy intensive industries which consumed more than 80% of the electricity in the year 2010. For that same year, aluminium factories consumed 73% of the total electricity produced and they are by far the largest consumers of electricity in Iceland. Residential sector consumed only 5% of the total electricity produced in Iceland in the year 2010.

Geothermal heat is used not only for producing electricity but is also used for the production of district heat. This district heat is used for various purposes but mainly for space heating in the residential sector (49%). In total, 89% of the space heating is covered by geothermal heat and the remaining space heating demand is covered by domestic oil-fired boilers (10%) and electric heaters (1%). During the production of electricity in geothermal power plants, large amounts of heat are wasted due to the low efficiency of such plants or around 12%. Not all of the heat needs to be utilized for district heat production and is therefore released to the environment.

Even though the energy hydro and geothermal resources in Iceland are large, they cannot be considered infinite and excessive production of electricity from these resources can have negative impacts on the environment and on the society. The utilization of these resources can therefore be unsustainable and the sustainable use of these renewable resources is discussed in this study. A master plan for hydro and geothermal resources has been developed in Iceland with the aim to get an overview of these resources and to rank them based on economical, social and environmental factors. This is a comprehensive project and in total 84 proposed new power plant options were ranked with a total electricity generation capacity of 47.5 TWh/year or around three times the electricity generation for the year 2010. Not all of these power plant options can be built and the master plan evaluates that the maximum electricity generation from geothermal and hydro resources is around 30TWh/year. Other options are considered to have larger negative impacts and are either on a waiting list if the negative impacts of those options needs to be investigated in more detail or they are on the list of unavailable options if these options are unfeasible. The maximum electricity generation from hydro and geothermal resources can however vary from the 30TWh/year since a discussion in the parliament in Iceland on these matters was not completed during the course of this project. Some options might therefore be moved to or from the waiting list and this procedure is hard to predict.

Recently, a discussion on exporting some of the excess electricity in Iceland to Europe has become louder and a transmission cable from Iceland to Europe is now considered both technically and economically feasible. Agreements have been made between Iceland and the United Kingdom on this matter and the two countries express their willingness to explore this possibility but the project is still in development phase. The cable would be around 1200km long and would be the largest submerged transmission cable in the world. The national power company of Iceland has published that the cable could support 700MW of power and could start operation by 2020.

Along with the possible introduction of a transmission cable from Iceland to Europe, increased demand for energy intensive industry in Iceland is also expected in coming years. These energy intensive industries have long term contracts on electricity demand and the contracts are made for 20 years or longer. By introducing a transmission cable to Europe while increasing the demand for energy intensive industries, a large part of the total geothermal and hydro resources could potentially be exploited in coming decades. This could mean that other resources than hydro and geothermal heat will have to be exploited in near future. With an installed capacity of around 2500MW in Iceland in the year 2010, the introduction of both a transmission cable to Europe and a new energy intensive industry will have large impacts on the Icelandic energy system.

In order to analyse the development of the Icelandic energy system, the concept of energy scenarios was used in this study. These energy scenarios were created based on the future development of the Icelandic energy system with special focus on the possible transmission cable to Europe and a further expansion of energy intensive industries. After having created the scenarios, the Icelandic energy system was implemented in the energy model BALMOREL which was then used to simulate these scenarios. The BALMOREL model is an optimization model that minimizes the cost for operating the energy system based on certain criteria. The model has been developed under open-source criteria and can be adjusted and changed according to the need of the user. Due to the complexity of the BALMOREL model, a good understanding of the model functionality is required for any changes to be made. The model served as a tool for analysing the development Icelandic energy system and as a result of the study, the model developed in this study can give a good idea of what the future might bring. The simulations show that investments in new power capacity are needed to meet the growing demand from the transmission cable and the energy intensive industries and that electricity generation from hydro and geothermal power plants could exceed the energy resource limits as given in the master plan for hydro and geothermal resources. This is of concern and means that power plant options in the waiting list of the master plan for hydro and geothermal resources could need to be exploited. For this to be avoided, other energy resources than hydro and geothermal heat will have to be utilized.

Based on the work presented in this study, the idea of using energy scenarios as a tool for analysis is extremely relevant when analysing the Icelandic energy system. This can be justified by the difficulties of predicting the development of the system when large consumers of electricity are introduced to the Icelandic system. The energy scenarios can be used to ensure that the development of the system is normal and that the hydro and geothermal resources are used in a sustainable way without compromising the needs of the population of Iceland and its future generations. The use of simulation tools as BALMOREL can furthermore help in this procedure and a foundation for this was established in this study.

10. Perspectives

The work presented in this study shows that energy scenarios can prove a useful tool to analyse the Icelandic energy system and its development in coming years. Several issues need however to be resolved before energy scenario analysis can be used in a more efficient way. Some of these issued are discussed in this section and potential projects based on the energy model developed during this study are discussed.

For an energy scenario analysis to be laid out, relevant data has to be collected and maintained in a database that can easily be accessed. Preferably this data should be easily downloaded from the internet in a convenient file format. During the course of the project, data collection was largely time-consuming and an easy access of relevant data could have largely eased such work. For using BALMOREL, large amounts of data are needed for the model to run and the data need to be organized properly for an efficient use of the model.

The BALMOREL model of Iceland created in this study can be improved with more detailed data. Iceland could be divided into more regions and areas and specific parts of the Icelandic energy system could be investigated. The heat demand can be introduced in the BALMOREL model of Iceland and its hourly variation profile. Specific geothermal power plants can be investigated and the waste heat can be minimized. The waste heat can be utilized for various industrial processes and this can be simulated using BALMOREL. The emissions from geothermal power plants can also be implemented in the model.

Projects that could be analysed by using the BALMOREL model include the increased penetration of wind into the Icelandic energy system or the introduction of electric vehicles. Hydro scheduling can be done by BALMOREL and the water levels in the reservoirs at each time can be optimized. The potential projects are extremely many and more will not be discussed here. It is however clear that the model allows for a great deal of projects that could prove relevant for Iceland in near future.

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12. Appendix

Aggregation of data into different sectors of the society was necessary and the aggregation is described in this section. In Iceland, the consumption of fuels is more divided on each consumer rather than to different sectors of the society and the objective of this aggregation is to divide all fuel consumption on three main sectors of the society; residential sector, industrial sector and tertiary sector. Consumption of oil in the transport sector and for the fisheries is also discussed. The aggregation is based on the references [12], [57] and [58]. These are the forecast for electricity report, consumption of geothermal heat and the forecast for oil consumption respectively and are published by the National energy Authority in Iceland. The data collection is different for each these references. In this section, the aggregation needed to be made in each sector is discussed.

Industrial sector

The electricity demands from utilities are placed in the industrial sector and also the electricity demand for fisheries and agriculture. The oil demand for the industrial sector includes energy intensive industries and other industries and a heating value of 42.5 MJ/ton of oil is assumed which is the average of all the fuels given in [58]. Geothermal heat for industry involves space heating only.

Residential sector

Electricity consumption for households only. Geothermal heat for snow-melting systems is in the residential sector. Oil consumption in residential sector is for residences and for swimming pools.

Tertiary sector

All data sources have tertiary sector separately and therefore no aggregation needed.

Transport

The transport sector covers all vehicles in Iceland except for the fisheries. The transport sector therefore covers: cars and equipment, airplanes (international and domestic) and ships and ferries (domestic freight and passenger). A heating value of 42.5 MJ/kg oil was used in the calculations.

Fisheries

The oil consumption of the fishing fleet covers the consumption from both domestic and international fishing ships.