Harvesting the Benefits of Iceland’s Energy Resources

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Abstract—Iceland is blessed with rich renewable energy resources in hydro, geothermal and wind. Wind is largely untapped, but a considerable part of the hydro and geothermal resources have been harnessed in the last few decades, mostly for local energy intensive industry (EII). The development has been massive and today, electricity consumption per capita is already, by far the highest in the world, exceeding the OECD average by a factor of almost 7. In spite of this extensive development, there is still room for further expansion, since only about a third of the available economical resources have been tapped. The remainder includes geothermal and hydro projects, categorized for environmental restrictions in the preservation and on-hold categories of the Master Plan (MP), as discussed further in the paper. In addition, almost all wind resources are completely untapped.

This paper assesses the potential economic benefit of marketing the renewable electricity of Iceland directly by export in larger markets, as opposed to selling them locally to the EII, which in the past has been the beneficiary of tapping these resources in this isolated power system. However, with maturing submarine link technology, it may well be economical to transmit and integrate these energy resources into EU or UK markets, thereby realizing the economic rent of these resources.

The assessment in principle is twofold. (1) First, a one-way, constant bulk transfer to the United Kingdom (UK) is possible, assuming purchase agreements with prices comparable to those paid to renewable or nuclear generators by the UK government in recent years. (2) Secondly a flexible transfer is briefly discussed, where the power flow may even alternate to and from Iceland and be variable, in line with market prices in the UK or hydro conditions on the Icelandic side. The paper estimates numerically the benefits in the first case, as the income from energy sales, minus the cost of generation and transmission across a submarine HVDC link to the UK or EU markets. The 2nd case remains to be investigated.

The main results are that the total economic rent is comparable to the total Icelandic state tax income per year, or around 2 - 5 Billion US$ per year, with fully developed hydro and geothermal schemes in Iceland, as further specified below. The question, who will reap these benefits, in addition to the resource owners, is an open one.

Key words: Energy resources, Economic rent, Electricity Markets, Geothermal electricity generation, Hydroelectricity, Renewable energy

I. INTRODUCTION

Iceland has currently by far the highest electricity generation by renewable energy resources of any country, when compared to the size of its current economy and population. Figure 1, shows this generation per capita in 2014 for several countries [1], where Iceland occupies the leftmost top position. This position has been reached in a 50 year development, started by the pioneers who introduced aluminum smelters in the power system in the late 1960s which has continued to this day.

Currently about 80% of the load is by local aluminum smelters and other EII, purchasing power by long term contracts. In addition the general load is currently based on tariffs. Since no real spot market is yet functioning, the trading is by bilateral contracts, where market participants compete for such contracts. However, an informal daily balancing energy market from hour to hour aligns the generation and consumption sides.

These resources and the associated benefits have recently come into focus in the Icelandic media due to the implementation of the EU 3rd energy package in the Alþingi (Parliament), as of this writing. As a member of the European Economic Area (EEA), Iceland has implemented the EU legislation from 2003, with the 1st "package" separating generation, transmission, distribution and sales. The 3rd package [3] is now in the process of being implemented as legislation.

The public debate on the package also involves High Voltage Direct Current (HVDC) links, potentially linking Iceland to the UK or other EU countries in the future.

As previously mentioned, this paper estimates the potential for realizing the economic value of the energy riches, by a direct bulk export of electricity through HVDC connectors. We estimate the economic rent of a one-way constant power transfer through such links and calculate this rent based on (a) local generation costs, (b) total size of the resources, (c) transmission costs per unit of energy and finally (d) unit prices which may be available from a purchaser in the UK.

The paper is organized as follows:

In Section II we will discuss in more detail the principles of realizing the maximum economic benefits of Iceland's energy resources.

In Section III we will discuss the extent and size of Iceland's energy resources with a detailed list of potential projects.

In Section IV we will discuss the transmission cost across a link, and assumptions on prices paid for the energy at the receiving end of the submarine link in the UK.

In Section V we will present the results and computations in estimating the maximum economic rent as outlined above.

Finally in Section VI we will present conclusions and discussion and implications of the results. Finally the paper is concluded with an acknowledgment section and list of references.

II. THE PRINCIPLES OF REALIZING THE RESOURCE BENEFITS

A key concept when realizing the economic benefits of any natural resources, such as energy resources, is the concept Economic rent. In the presence of a well functioning market for the product from these resources - in this case electricity - the concept can simply be calculated as the difference between the income from sales in the market, minus the cost of generating and bringing the product to the market. In the absence of such a market, the economic rent can still be calculated by comparing with the state of affairs, if the resource in question would not exist, and one had to resort to an alternative, more expensive option.

Now consider this concept economic rent and the application of it, when getting electricity to a distant market through a transmission link. There exist at least two different methods to bring the electricity to the market in terms of operating a HVDC transmission link. These are discussed in the next subsection. But first a word on the origin and meaning of this concept.

A. Economic rent and renewable energy resources

The concept economic rent is originally from [9]. It is basically the profit from an access to a scarce resource, above the regular return. The formula below shows this principle for the rent, with an electricity market.

\[
\text{Economic rent} = \text{Income from energy sales} - \text{Generation cost} - \text{Transmission cost}
\]

In this formula’s right side, the income is calculated per time period, such as a year, in selling in a spot market. For the same period, the generation costs consists of investment and operations cost, with proper depreciation or annuity, by standard accounting procedures. Finally the transmission cost should be based on actual regulated tariffs for the link [10] or calculated from investment and operations cost of that link.

B. Bulk or dynamic energy transfers and trade

Currently in Iceland there is a rather weak local electricity market, in terms of how well the market realizes a true market value, when participants bid/offer their product freely. The current market is mostly based on bilateral long term local contracts for bulk EII loads. Therefore a properly designed, and functioning spot market is essential to unleash the market forces, which could then interact with distant markets through a link.

However, without a local spot market, but with HVDC links, it may still be possible to bring the product to larger markets, such as the UK or EU markets with bilateral contracts. It is conceivable to sell bulk energy in a one-way power flow, according to such a contracts. This method is the main topic of this paper. Alternatively, with a distant spot market, it would be possible for generators in Iceland to sell in such a market, in each time step such as an hour or 30 minutes, some energy, according to a given strategy and the current or expected prices in the spot market.

Therefore, we have in principle at least 2 different approaches of operating future submarine links to distant electricity markets.

1) Constant, bulk flow. This assumes constant one-way power flow and sales to a buyer according to a long term contract with the associated price and quantity

2) Dynamic, back and forth flow. This arrangements assumes a variable two-way power flow which may change direction from hour to hour, and sales depending on the sellers strategy and expected spot market prices.

Of course a given link may be partitioned, so a part of its capacity operates in each mode.

Again, in this paper, we will study primarily the first case above (Constant bulk flow) where a hypothetical constant flow or amount of energy from the Icelandic energy resources, is transmitted, as outlined in the next section.

III. THE ICELAND ENERGY RESOURCES

Table I shows a summary of the Icelandic hydroelectric and geothermal resources for electricity generation, in excess
of the general demand [11] to homes and small businesses. The 1st row shows the current generation 15.661 TWh/year in 2017, mainly for the EII load. The total consumption was 18.267 TWh/year of which EII load was 14.870 TWh/year or 81.4%. Adding losses, this amounts to 19.239 TWh/year. Therefore, with proportional distribution of losses, the total current generation in 2017 for EII was 15.661 TWh/year including losses. The remaining rows show possible future generation from projects in environmental categories of the Master Plan (MP) [12], as outlined below.

Next we will go into more detail and list the projects in each category of the MP and explain the concept of the above mentioned categories. These are formed in such a way that all available processes projected by the MP are allocated to the three following categories:

1) **The Utilization Category.** In this category are projects which are deemed fit for construction. Table II lists the projects in the Utilization Category.

2) **The On-Hold Category.** Projects are placed in this category when a position can not be taken by the MP due to lack of data. Table III lists the projects in the On-Hold Category.

3) **The Protection Category.** Finally, projects are placed in which are not deemed right for construction by the MP committee. Table IV lists the projects in the Protection Category.

Finally Figure 2 summarizes graphically the data given in Tables II III and IV along with Table I. The Figure shows, on the vertical axis, the unit cost in each category for each projects, as a stepwise increasing curve within each category. The unit cost in Figure 2 (In US$/MWh), includes connection cost and OPEX, according to the MP. The shaded areas indicate the average cost and quantity within each category, as also reflected in Table I. The unit costs are also shown in column 9 in Tables II III and IV. Within each category the projects are sorted according to this unit cost, both as shown in these Tables and in Figure 2.

Therefore the total size of the resources in all categories, including existing generation amounts to 51.47 Twh/ year with the average generation unit cost of 27.3 US$/Mwh amounting to a total of 1.4 Billion US$/year total annual generation cost.

### Table I: Summary of accumulated capacities, and unit costs and total annual cost summarized for current generation for the EII and all categories of the MP [12]. Row 1 is the current generation in excess of general demand [11]. Also the summaries for all 3 categories are shown, i.e. summed up for projects in all categories.

<table>
<thead>
<tr>
<th>Energy &amp; Type</th>
<th>Region</th>
<th>Catchment / geothermal area</th>
<th>ID # in 2nd phase</th>
<th>Project name</th>
<th>Installed capacity in (MW)</th>
<th>Energy output (GWh/year)</th>
<th>Generation unit cost (US$/MWh)</th>
<th>Total annual cost (MUS$/yr)</th>
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<tbody>
<tr>
<td>1</td>
<td>Hydropower</td>
<td>South Iceland</td>
<td>Kjósá</td>
<td>1</td>
<td>Hvammsvirkjun</td>
<td>29</td>
<td>82</td>
<td>166</td>
</tr>
<tr>
<td>2</td>
<td>Hydropower</td>
<td>North Iceland</td>
<td>Bliða river</td>
<td>5</td>
<td>Blönduölf</td>
<td>20</td>
<td>131</td>
<td>29.1</td>
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<td>Heiðstafjarðar</td>
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<td>Heiðstafjarðar</td>
<td>180</td>
<td>1476</td>
<td>32.4</td>
</tr>
<tr>
<td>4</td>
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<td>Námafjall area</td>
<td>97</td>
<td>Bjarnarfljót</td>
<td>90</td>
<td>738</td>
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</tr>
<tr>
<td>5</td>
<td>Geothermal</td>
<td>North East Iceland</td>
<td>Krafla region</td>
<td>103</td>
<td>Krafla I, 2, phase</td>
<td>90</td>
<td>738</td>
<td>33.8</td>
</tr>
<tr>
<td>6</td>
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<td>North East Iceland</td>
<td>Krafla region</td>
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<td>Reykjanesskagi</td>
<td>61</td>
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<td>Heiðstafjarðar</td>
<td>105</td>
<td>Heiðstafjarðar</td>
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<td>99</td>
<td>Krafla I, expansion</td>
<td>45</td>
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<tr>
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<td>Ölfljótsfjarður</td>
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<td>Eldborg</td>
<td>50</td>
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<tr>
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<td>Hengill area</td>
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<td>Grúðarhúsi</td>
<td>45</td>
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<td>45</td>
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<td>90</td>
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<tr>
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<td>Krossahl</td>
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<td>Sandfell</td>
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<td>Krossahl</td>
<td>66</td>
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<td>Reykjanesskagi</td>
<td>62</td>
<td>Snæfells</td>
<td>40</td>
<td>338</td>
<td>41.2</td>
</tr>
</tbody>
</table>

Hydropower: 3 projects, Geothermal: 14 projects

The Utilization Category

The On-Hold Category

The Protection Category

A. **Other Assumptions in Cost Calculations**

1) **Operations cost (OPEX)** including maintenance. We assume operations cost per year as a fraction of construction cost to be 3% for geothermal projects and 1% for hydro projects. This is in line with assumptions traditionally used in the Icelandic power system planning. For submarine links we assume 3.5% OPEX per year.

2) **Interest rate.** A 3% interest rate is used when calculating the annual cost from investments, but results are discussed later for 5% and 7% interest rates.

3) **Salvage value.** A 15% salvage value is used for geothermal projects and a 20% salvage value is used for hydro projects. No salvage value is assumed for submarine links.

4) **Economic lifetime** A 20 year lifetime is used for geothermal projects, while a 35 year economic lifetime is assumed for hydro projects. A 25 year lifetime is assumed for submarine links.

5) **Investment cost.** All costs are according to the approximate cost data from the MP, phase 2 [12, 13] based on cost groups for unit costs, as shown at left in Table V. These costs are updated from the MP date of publication, using indices from Statistics Iceland [14], as shown at right in Table V.

6) **Rates of exchange.** The rate of exchange of a US$ against a Great Britain Pound (GBP) is 1.3044 US$/GBP. In addition we assume the rate of exchange for a Euro (EUR) against the US$ of 1.13 US$/EUR. The rate of exchange for the US$ against an Icelandic krona (ISK) is 122 ISK for a US$.
Table III: Power projects in the On Hold Category of the MP, phase 2. See the Master Plan web site: http://www.ramma.is/english/the-master-plan-today /current-master-plan/ and detailed information in Figure 2 of reference [10]

The table below shows the accumulated capacity (TWh/year) and the unit cost (USD/MWh) of the projects currently on hold. The projects are listed by region and type of resource, with additional information on the investment cost for MP phase 2.

Table IV: Power projects in the Protection Category of the MP, phase 2. See the Master Plan web site: http://www.ramma.is/english/the-master-plan-today /current-master-plan/ and detailed information in Figure 2 of reference [10]

The table below shows the protection projects currently under consideration, with additional information on the energy output (GWh/year) and the total annual cost (USD/MWh).

Table V: The cost groups [12] (At left) for projects and the indices (At right) used for updating the investment cost for MP phase 2. The figures used in this study are shown in bold.

The table below shows the cost groups and their corresponding indices for updating the investment cost for MP phase 2. The indices are shown in bold to indicate their importance.

Figure 2: The estimated cost structure of Iceland's hydroelectric and geothermal energy resources, ranging from existing projects (Shown at left), utilization, on-hold and protection categories, that i 3 categories of potential future projects, shown at right in the Figure with different shades of grey. Within each category the unit cost for individual projects is shown as a stepwise increasing function, indicating the rising unit cost of the projects, sequences with rising costs, including connection cost. The existing generation is in excess of general demand, and is approximately 15 TWh/year. Average generation cost estimated rather arbitrarily to be 20 US$/MWh. The average costs within each category is shown in the Figure as vertical height of the grey shaded boxes and in Table I.

7) Connection cost. For each project, a certain connection cost is included. For details of the cost calculations see the MP and Figure 2 in [10].

IV. TRANSMISSION COST AND MARKET PRICE

In this section, assumptions on the cost of transmission through HVDC submarine links will be described. Also, the market prices in the UK will be discussed, both the spot prices in recent years and the prices paid to renewable and nuclear generation in the UK will be discussed briefly. Also we will touch upon the possible discussion between the Icelandic and UK government or other parties.

A. Transmission cost across UK-Iceland submarine links

An HVDC submarine link between Iceland and the United Kingdom has been studied in decades [15]. One of the most important results of this particular link is [16, 17, 18]. Unfortunately, [16] contains very sparse cost data, for instance with no operation costs information. Another recent and interesting study on such links, with considerable cost data is [19].

In this paper we use data for the interconnector from [16, 17] and other sources. In [16], Chapter 17, Figure 116, the total cost of the 1200 km cable with 1000 MW transmission...
capacity, including enhancements to the AC transmission system on the Icelandic side, is estimated to be 3200 to 3400 Million EUR. Using 3300 Million EUR as median value and with 8000 h/year utilization time, assuming constant one way flow. We use 3% basic interest rate with deviations to 5% and 7%. Then the following figures are obtained:

$$A = \frac{rP}{1 - (1 + r)^{-N}} = \frac{0.03 \cdot 3300}{1 - 1.03^{-25}} = \frac{99}{0.5224} = 189.51$$

where $A$ is the annual (Annuity) cost, $P$ is the investment, $r$ is the interest rate and $N$ is the project life time. Therefore the annuity cost is 189.5 Million Eur/Year. Adding an Operations and maintenance cost (OPEX), given the need to repair the cable in case of breakdown, we use a cost figure assumed to be 3.5% per year of construction cost, or 115.5 Million Eur/Year. This results in the total annual cost of transmission across the cable, of

$$A_{tot} = A + A_{OP} = 189.5 + 115.5 = 305.0 \text{ Million EUR/year.}$$

where $A_{OP}$ is the annual operations cost. By assumptions, the annual energy transmitted is:

$$E = P_t \cdot h = 1000 \cdot 8 = 8000 \text{ Gwh/year}$$

where $h$ is the utilization time and $P_t$ is the transmitted power. Therefore the unit transmission cost is:

$$k_T = \frac{A_{tot}}{E} = \frac{305000[\text{Thousand Eur}]}{8000[\text{Thousand Mwh}]} = 38.1 \text{ Eur/Mwh}$$

With the rate of exchange for EUR against a US$ of 1.13 US$/EUR we get:

$$k_{TUS}$ = 38.1 \cdot 1.13 = 43.0 \text{ US$/Mwh}$$

This is the price used in the calculation and the results as discussed in Section V.

B. Prices in the UK paid to renewable generation

In this subsection we discuss potential prices for carbon free renewable energy, that might be transported from Iceland in light of the prices that have been paid to renewable or nuclear generation in the UK. Such prices might for instance have been taken up in negotiations between the U.K. and Icelandic government in recent years, although they may not have not been published.

Such prices have been discussed to some extent in blogs and media in Iceland [20, 21, 22], but unfortunately, they are to a large extent of a speculative nature since they have not been officially confirmed. In addition, news media in the UK [23] report of guaranteed prices, such as the minimum price of 92.5 GB£/Mwh to be paid by the Government to Hinkley Point C Nuclear station.

For instance the following quotation on prices paid to renewable generation is from [24]:

"...In 2015, two offshore wind projects were awarded contracts at £120 and £114 per megawatt hour (Mwh). Two and a half years later, two projects are priced at £58/MWh, while a third is £75/MWh. This is a 50% fall in the level of subsidy and makes offshore wind significantly cheaper than new nuclear power (the equivalent contract for Hinkley Point C is around £93/MWh)...".

In this paper we use prices in the UK ranging from 70 to 160 GB£/MWh, as shown below in row 8 in Tables VI and VII as discussed further in Section V.

C. Market prices in the UK

As discussed above in Section II-B, it is possible to have a flexible interchange of power flow, by trading in a spot market or power exchange, for instance in the UK. Therefore we also look at short term market prices in the U.K market.

Average prices in the UK whole sale market in the last few years have ranged from 40 to 100 GB£/Mwh as shown in Figure 3 of [25] and extended in Figures 3 and 4.

Furthermore, Icelandic hydroelectric power and large reservoirs can take part in alleviating the instability in UK wind generation, an example of which is shown in Figure 5. In order to estimate the benefits of such short term market participation, a special simulation/optimization model is needed to address questions related to this trading, such as this authors approach in [25]. As previously stated, this flexibility os not the topic of this paper and will therefore not be discussed further.

Finally, it should be reiterated that on the Icelandic side of potential submarine links, a functioning spot market or electricity exchange does not yet exist.

We now turn to the principal findings of this paper.

V. PRINCIPAL RESULTS AND CALCULATIONS

The principal results are shown in Tables VI for prices in the UK ranging from 70 to 160 GB£/MWh. It shows the calculation for rent, assuming full exploitation of projects in the utilization category and also On-hold category. Therefore it
Table VI: Power Scenarios without the Protection Category, labelled A,B,C,D,E,F,G,H and J across market prices in the UK, ranging from 70 to 160 GB/Mwh, as shown in row 8. Therefore the shaded parts of the table show the variable assumption and the associated variable results. Values in row with label "1" is from reference [11].

Table VII: Power Scenarios with the Protection Category, labelled K,L,M,N,O,P,Q,R,S and T across market prices in the UK, ranging from 70 to 160 GB/Mwh, as shown in row with label "K". Therefore the shaded parts of the table show the variable assumption and the associated variable results. Values in row with label "1" is from reference [11].

The former Table shows that the benefit ranges from approximately 1 - 5 Billion US$ per year for all resources except the Protection category, while adding this category will increase this benefit or rent to the range of approximately 1 - 7 Billion US$ per year.

One interesting aspect is to compare the results to all income taxes to the Icelandic State. The last row in both tables shows that the fraction ranges from about 15% to 138%. Therefore one can say that the maximum benefit is comparable to all state taxes in Iceland.

In the calculation Matlab [27] has been used.

VI. Conclusions and Discussion

The main conclusions of the paper can be summarized as follows:

- The paper estimates the bounds on the economic rent of Iceland’s energy resources, given their market price and quantity. In the future there will likely be a competition among the parties to capture a part of this rent. Generally,
parties harnessing such a rent should share it in some reasonable proportions. For the rent to remain largely with the resource owners in Iceland, there must be the proper regulation and legal environment in place.

- Given the assumptions of prices paid to the carbon free renewable generation from Iceland in the range of 70-160 GB£/Mwh, the expected economic rent from the trade should be in the range of 1-5 Billion US$ per year without including hydro and geothermal projects in the Protection category. For instance, assuming the price in the UK of 100 GB£/Mwh the benefit according to Table VI (Column D, row 11) should be around 2.23 Billion US$ per year or 272.5 Billion ISK/yr.

- By adding the Protection category the expected benefit or rent should increase to approximately 1-7 Billion US$ per year. For instance, again assuming the UK price of 100 GB£/Mwh the benefit according to Table VII (Column D, row 12) will be 3.06 Billion US$/year or 373.4 Billion ISK/yr.

- By increasing the interest rate from 3% to 5%, the above figures, for the UK price of 100 GB£/Mwh, will be reduced to 227 and 311 Billion ISK per year, respectively.

- Furthermore, increasing the interest rate further to 7% the above figures, for the UK price of 100 GB£/Mwh, will be reduced to the range of 179 to 205 Billion ISK/yr, respectively. Note that the above Tables in this paper are only shown for the case of 3% interest rate per year.

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REFERENCES


