Environmental Considerations and Transmission Planning in a Renewable Power System

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***Abstract*—Iceland is rich with geothermal and hydro energy resources in addition to unique natural conditions that attract a rapidly increasing number of tourists. All these factors will play an important role in the future economy and therefore a trade-off is needed to accommodate all aspects, that may in certain circumstances be considered mutually exclusive. The transport of electrical energy to load centers will require future expansion the electric transmission system, the responsibility of the national grid operator, Landsnet. However environmental constraints play an increasing role in both the generation and transmission expansion process, due to tourism and preservation concerns. To reach a consensus in generation expansion, the Government Master Plan (MP) is currently in progress in its 3rd phases with allocation of various hydro or geothermal projects into the preservation or utilization categories. In transmission expansion planning, similarly, Landsnet has recently published its new, system wide plan to consolidate the conflicting views of where and when transmission expansion steps can be taken, in order to meet the future transmission requirements, but at the same time avoid environmentally sensitive areas. These steps are principally, of course, in the form of viable overhead line and/or underground cable routes and options.**

This paper examines the transmission planning options that are available, including those in the Landsnet system plan. The main topic and purpose of the paper is to describe, review and discuss these plans, in the light of securing necessary future energy supply, but still be able to reach a consensus that respects environmental concerns and the needs to preserve for instance sensitive natural parks and attractions for future generations. New technologies and transmission capacities or options, such as overhead lines and underground cables, will be examined, both in different load zones and transmission corridors, in the light of established load forecasts and the generation options that are currently in the MP and its utilization category. The paper also discusses the need for robustness in planning, as the forecasts and generation options in each category will be subject to currently unknown changes in the future. These changes may stem from changed political climate and/or arrival of new customers such as with future interconnections to external markets and new local energy intensive customers. Here the possibility of the shutting down the facilities of old customers, must be borne in mind.

I. Introduction

The main power transmission system in Iceland is currently operated by Landsnet, the National Grid Co of Iceland. Landsnet was established in 2003 on the basis of the then new Electricity Act separating the generation or competitive and transmission or monopolistic activities. Its mission was to operate Iceland's electric power transmission system. Landsnet owners and their shares are currently as follows:

- Landsvirkjun, [The National Power Company], 64.73%
- Rafmagnsveitur ríkisins or RARIK [The State Electric Power Works] 22.51%
- Orkuveita Reykjavíkur [Reykjavik Energy], 6.78%
- Orkubú Vestfjarða [The Westfjord Power Company], 5.98%

Prior to Landsnet's founding, the transmission system planning and operation in Iceland resided with Landsvirkjun, which was originally founded in 1965, and responsible for both the main generation and transmission system until Landsnet's founding.

This paper's purpose is to review some basic aspects of transmission planning as well as the available transmission options, including the Landsnet system planning options. These options must meet the criteria of securing the energy supply, and various technical constraints, but still conform to environmental concerns and needs. In addition, the possibility of direct export of energy to neighboring markets must be kept in mind [1, 2] as a future possibility. New transmission technologies, such as viable underground cables, will be examined, considering available corridors and generation options, for instance those that have been passed by the Master Plan [3] as belonging to a utilization category.

Therefore, the paper is organized as follows:

- In Section II we discuss some basic aspects of transmission planning as well as the planning of the Icelandic transmission system and its zoning. The Landsnet control center and its main aspects are briefly reviewed, and finally assumptions such as scenarios and load cases are reviewed.
- In Section III we present and discuss the basic choices between underground cables and overhead lines, where underground cables can serve as a new technology in the context of the main Icelandic transmission system.
- Section IV presents the major results and discussions and conclusions, for instance the conclusions reached by the Landsnet Transmission System Plan (LTSP) [4].
- Finally the paper is concluded with a references section.

978-1-5090-4650-8/16/$31.00

II. THE TRANSMISSION SYSTEM AND ITS ZONING

A. Transmission system characteristics and zoning

Figure 1 shows a map of the main system network, together with useful zoning, that is areas or parts of Iceland used in planning studies, such as the LTSP, as described in this paper. The current highest operating voltage is 220 kV shown as thick black lines in the South-West and in the East, but a bulk of the system has the operating voltage of 132 kV (Thinner grey lines). The most recent additions in the South-West are designed and constructed to be used later at 400 kV, but presently operated at 220 kV. In addition, there are regional distribution networks at lower voltages owned and operated by other electrical utilities. The lowest voltage in the Landsnet system is 66 kV, with a few exceptions with 33 kV.

Figure 1 also shows the eight geographical zones, denoted as follows and shown "boxed" in the Figure. These zones are convenient to be viewed as a network with nodes, representing certain areas lumped together and transmission corridors between these nodes (areas).

The zones are defined as the following:

1) HB (The capital Reykjavík and surrounding communities and vicinity)
2) SN (Reykjanes peninsula)
3) N (The North)
4) NA (The North-East)
5) A (The East)
6) S (The South)
7) V (The West)
8) VF (The West-fjords)

The zones are useful to represent lumping of all apparatus and lines in a given part of the country for transmission planning purposes, with power flow in the corridors between zones, as mentioned previously, see also [4].

B. Basic aspects of transmission planning

Figure 2 indicates that the framework for basic transmission planning, can be viewed as a *network*, where the objective may be to find the expansion schedule, which minimizes the total cost, subject to various technical, security, environmental and other constraints. This problem may be stated as an optimization problem, with an objective function and constraint. Here we will, as an example, state an objective function for an *integer linear programming* problem (ILP), and list possible types of constraints. The ILP problem therefore centers around a network, as shown by Figure 2. Other methodologies are numerous, such as those based on evolutionary computation [5].

Assume we have a network with N nodes and N_B branches and let $\Omega_B = \{1, 2, ..., m, ..., N_B\}$ be the set of branches representing available corridors. Let $t = 1, 2, ..., T$ represent a time index, for instance in years, with a planning horizon of T units (years). Furthermore let $\Omega_m = \{1, 2, ..., i, ..., N_{P,m}\}$ be a set of available transmission *expansion options* (EO) for corridor number m, where the number of these option available in corridor m is $N_{P,m}$. These may be different cable types, and overhead line designs, with different, appropriate voltage levels, etc. and their number may be corridor specific. The characteristics of these EO's, such as cost and power transmission capability is assumed known and constant.

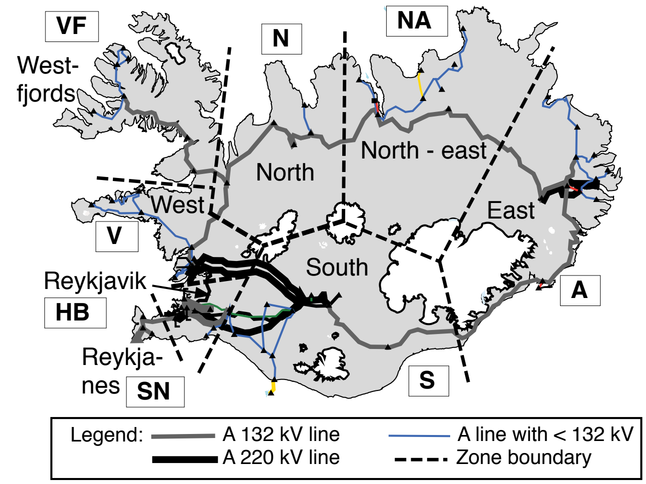

Figure 1. The main transmission system in Iceland with 220 kV lines, shown as a cluster of thick black lines and 132 kV lines, shown as thinner grey lines. Note the concentration of the 220 kV grid in the South-West and when connecting a large aluminum smelter in the east, while the main ring connection is 132 kV. The Figure also shows the zones, designated by the boxed letters, separating the parts or areas of the country. This Figure is adapted from Figure 3-6 in [4].

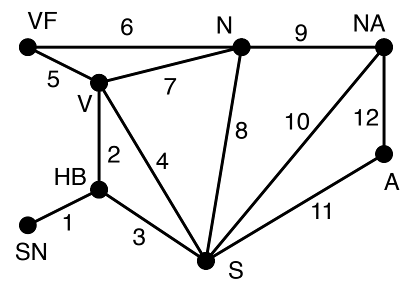

Figure 2. A simple network useful for modeling and planning purposes, representing the $N = 8$ zones or *nodes* of the Icelandic transmission system in Figure 1, with a numbering scheme assigned to the transmission corridors or *branches*. The number of branches in this example are $N_B = 12$. Note that branch number 8 between zones N and S may not presently be a practical corridor, as indicated in Figure 9, but may later become an optional corridor in future planning.

Therefore, let $C_{m,i}$ be the given total discounted cost, at the time of construction - including operations cost and salvage value at the end of the planning horizon - of constructing transmission expansion option (EO) number i in corridor m. And let $u_{i,m,t}$ be a binary variable where $u_{i,m,t} = 1$ if an EO of type i is constructed in corridor m at time t, and let $u_{i,m,t} = 0$ otherwise. Finally let α be the continuous time discount rate.

Then an objective function for the transmission planning ILP problem can be defined as follows:

$$P^* = \min_{u_{i,m,t}} \left\{ \sum_{t=1}^{T} \sum_{m \in \Omega_B} \sum_{i \in \Omega_m} u_{i,m,t} C_{m,i} \exp(-\alpha t) \right\} \quad (1)$$

where $u_{i,m,t}$ are the zero/one variables and other quantities are known constants. P^* is a minimum total discounted cost and a discount factor has been included for each term in (1).

The constraints can be varied - and it is beyond the scope this paper to formalize and list all such relevant constraints, of course depending on the exact problem formulation at hand. However, the following list will give an indication of the type of the most common constraints, where these may call for additional variables and constants (For instance phase angles and voltages) to be included in the objective function but perhaps mainly in the constraints. These can be as follows:

1) Power flow equation and constraints (linear, quadratic or AC power flow) and power balance.
2) Maximum power flow constraints.
3) Voltage stability and voltage magnitude box constraints.
4) Transient and dynamic stability constraints (Limiting the number of available integer combinations).
5) Continuity equations (Kirchoff's law) for each node.
6) Combination constraints on integer variables.
7) Other relevant constraints!

Furthermore, the planning problem can be expanded by considering, for instance, robustness and assuming stage-wise planning, that is the planning horizon is expanded in stages. Further discussion on this aspect and other aspects of the optimization problem (1) is beyond the scope of the paper, but it is shown here in order to bridge any potential gap between "theoretical" and "practical" transmission planning philosophies.

We next turn to describe the actual planning effort in the Icelandic transmission system.

C. Actual transmission planning in Iceland

Transmission planning in Iceland mainly dates back to Landsvirkjun's establishment in 1965, although power lines were of course planned earlier. A large step was taken by initiating construction of the ring connection with a series of 132 kV lines forming a ring around Iceland in 1972, thereby interconnecting the different rural areas, which had been previously operated in isolation. Landsvirkjun took over this ring line in 1982, when the company was expanded by a merger with Laxárvirkjun, a generating company in the North. A study on the "Southern line" was conducted [6] as apart of the line being taken over by Landsvirkjun. It resulted in closing of the "ring" connection, and the last part of the ring-line was taken into operation in 1984, with the 250 km line from Sigalda hydro station in the central highlands to Höfn. The line is 132 kV in Figure 1 connecting the S and A zones.

"Kerfisáætlun" stands for Landsnet Transmission System Plan (LTSP), and these studies have, according to the Landsnet web site, been carried out since 2004. The current plans are described in the LTSP, 2014-2030 [4] and this document will be discussed at some length in this paper.

D. System control

The main transmission and generation system is operated from the Landsnet Control Centre in Reykjavík, where a control and communication network is used to control and monitor the power system from a central location. The Control Centre oversees both the major generation stations, such as those of Landsvirkjun, and the transmission network in the Landsnet system and neighboring distribution systems. In addition, distribution utilities and energy intensive industry customers are a part of these control and monitoring activities.

E. Assumptions for the LTSP

Two basic assumptions for expansion plans in the LTSP are (a) the electrical forecasts by the official Energy Forecasting Committee (EFC) from 2013 [7] and (b) the Government "Rammaáætlun" or Master Plan (MP), phase II (also called Master plan) [8, 3]. In the current MP, about 16 hydro and geothermal projects are declared to belong to a *utilization category*. These are 14 geothermal projects and 2 hydroelectric projects. In addition to generation, it is important to have an assumption for the *location* of new load, such as Energy Intensive Industry (EII) load.

These basic assumptions are used in the LTSP to define 3 *scenarios*, each 10 years into the future: Scenario 1, or the "*zero scenario*", assumes a basic forecast, without any new EII load. The other two scenarios, number 2 and 3, assume new generation from the utilization category of the MP, either 50% og 100% of the installed capacity of all the projects in this category. For each scenario, about 2 to 3 different load cases were defined.

Figure 3 shows the capacity in MW for the 16 projects and a breakdown into to the eight zones - the parts of the country. For instance, 535 MW of new geothermal generation is available in the NA zone. Furthermore, Table I lists all these projects, or 2 hydropower projects and 14 geothermal projects. Note that these future projects are *in addition* to the present and existing generation system as shown in Figure 5.

Table I
THE 14 GEOTHERMAL AND 2 HYDROPOWER PROJECTS IN THE UTILIZATION CATEGORY THE MASTER PLAN, 2ND PHASE [8].

Type of energy	Zone	Catchment / geothermal area	# in 2nd phase	Name of power plant	Installed capacity (MW)	Energy generation (GWh/yr)	Cost group
Hydro	VF	Ófeigsfjörður	4	Hvalárvirkjun	35	259	5
Hydro	N	Blanda	5	Blönduveita	28	180	4
Geoth.	SN	Reykjanes area	61	Reykjanes	80	568	2.5
Geoth.	SN	Reykjanes area	62	Stóra-Sandvík	50	410	2.5
Geoth.	SN	Svartsengi area	63	Eldvörp	50	410	3
Geoth.	SN	Krýsuvík area	64	Sandfell	50	410	3
Geoth.	HB	Krýsuvík area	66	Sveifluháls	50	410	2
Geoth.	HB	Hengill area	69	Meitillinn	45	369	3
Geoth.	HB	Hengill area	70	Gráuhnúkar	45	369	3
Geoth.	HB	Hengill area	71	Hverahlíð	90	738	3
Geoth.	NA	Námafjall area	97	Bjarnarflag	90	738	2
Geoth.	NA	Krafla region	98	Krafla I, expansion	40	320	2
Geoth.	NA	Krafla region	99	Krafla II, 1. phase	45	369	2
Geoth.	NA	Krafla region	103	Krafla II, 2. phase	90	738	2
Geoth.	NA	Þeistareykir area	102	Þeistareykir	180	1,476	2
Geoth.	NA	Þeistareykir area	101	Þeistareykir west	90	738	2
TOTAL					1058	8,502	

F. Congestion in corridors between zones

In the LTSP, Landsnet defines 3 congested flows and their maximum capacities. These are shown as "cuts" in Figure 4,

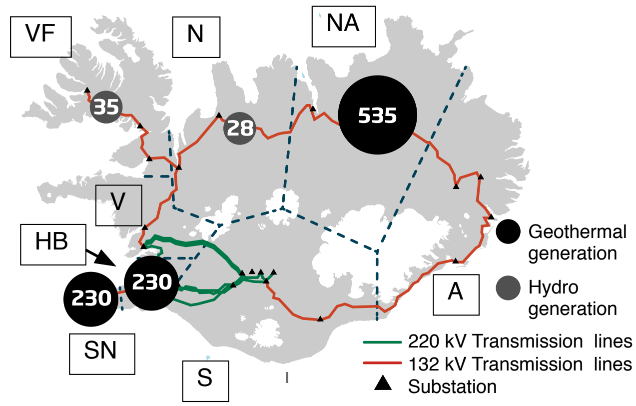

Figure 3. Generation capacity in Megawatts (MW) in different zones according to the utilization category of the MP, phase II [8]. The total is $535+230+230+28+35 = 1058$ MW as shown in Table I. Adapted from [4].

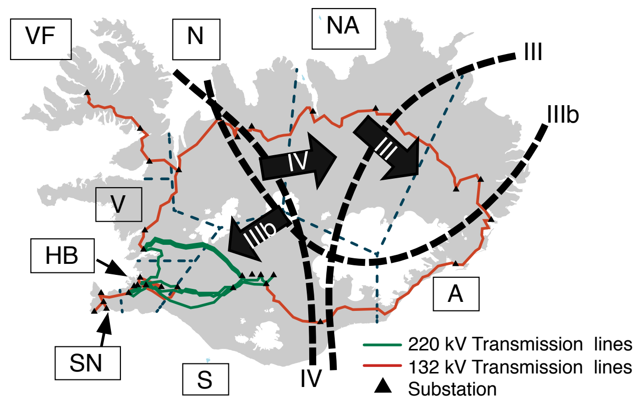

Figure 4. An example of *cuts* used in the planning study for transmission corridors between zones - based on the Master plan (MP), phase II [8]. Adapted from Figure 3.3 in [4].

which serves as an example of the analysis carried out in the LTSP. A complete discussion is beyond the scope of this paper, we refer to [4] for further details.

G. Scenarios and load cases

Next we discuss the definition of the scenarios and load cases as presented in the LTSP as a basis for the transmission planning study and policy paper. Three scenarios are defined and examined called 1) "Zero system", 2) "50% Master Plan" and 3) "100% Master Plan" described as follows:

1) Zero system: Load and generation is according the load forecast for the year 2023 [7]. No additional generation or EII load is assumed in this scenario.
2) 50% Master Plan [8]: This scenario uses the same basis as in the zero system but 50% of the Master Plan projects are implemented (A little more than 500 MW).
3) 100% Master Plan: This scenario uses the same basis as in the zero system but 100% of the Master Plan projects are implemented (A little more than 1.000 MW).

In addition, three different load cases or options are studied, here labelled A, B and C, as follows:

- A. Equal distribution between all 8 zones or 62.5 MW in the 50% Master Plan Case (A total of 500MW) and 125 MW in the 100% MP cases (A total of 1000 MW).
- B. Proportional distribution of new load according to new generation: The load is distributed proportionally among the zones according to new generation in the MP within each zone. This means that new EII load is located near new generation.
- C. All new load located in one zone: (500 or 1,000 MW), irrespective of the location of new generation.

Table II shows a summary of these scenarios and load cases in the LTSP [4] and Figure 9 shows the 8 zones and the main transmission corridors, with various configurations for the three load options A, B and C.

In each of the load generation scenarios and the associated transmission corridors, there is a choice between the options of constructing overhead lines or laying underground cables, which then, for the purpose of this study, constitute a novel transmission technology. Although the overhead line option is generally less costly, there may be a need to consolidate environmental concern for instance due to "visual pollution" of overhead lines. Therefore, laying an underground cable may be preferred. This has especially entered the political debate for the most appropriate expansion of branch/corridor number 10 across the highlands.

Thus, in the next Section we will discuss the pros and cons of underground cables vs. over-head lines, before discussing the results of the scenario/load combinations as presented in Table II, since these results will be discussed below in Section IV.

Table II
A SUMMARY OF LOAD CASES AND SCENARIOS IN THE LANDSNET LTSP [4] TRANSMISSION PLANNING ANALYSIS.

Load Distribution / Scenario	A	B	C
1	General increas according to load forecast		
2	500 MW load distributed equally in all zones	500 MW load distributed proportionally between zones axxording to generation	500 MW load in one zone
3	1000 MW load distributed equally in all zones	1000 MW load distributed proportionally between zones axxording to generation	1000 MW load in one zone

III. COMPARING UNDERGROUND CABLES AND OVERHEAD LINES

A part of the Landsnet Transmission System Plan (LTSP) [4] deals with life cycle cost comparisons between overhead lines and underground cables, based on, for instance, conditions in the ground for laying the cables, cable costs and other factors. Considerable uncertainty is in the investment and operating costs of both alternatives. The major conclusions of

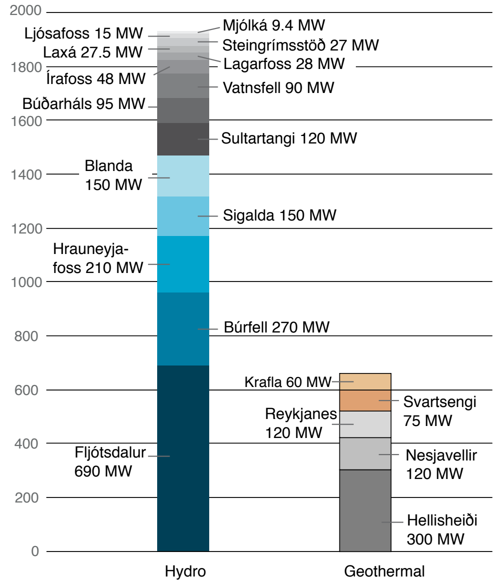

Figure 5. Installed capacity in MW in power plants of the major generators connected to the transmission system, at the beginning of the year 2014 in hydro and geothermal power stations in Iceland. This capacity was a total of 2592.9 MW and the break-down is shown in the Figure, which serves as a basis for the transmission planning analysis of [4]. This Figure is adapted, translated and redrawn from Figure 3-1 in [4] .

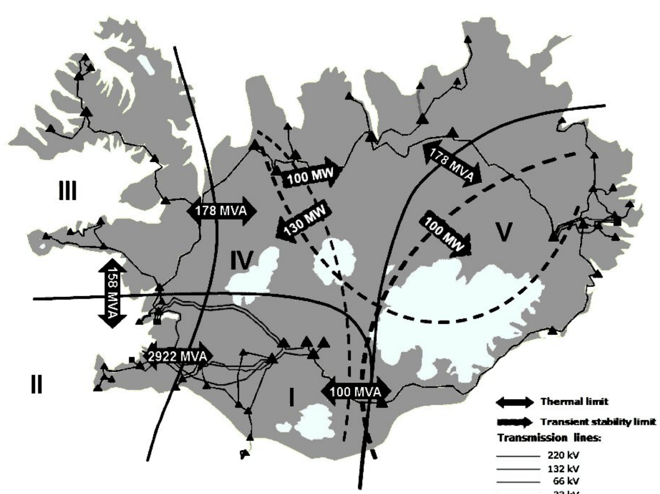

Figure 6. Present interconnections and power exchanges between transmission zones in Iceland in 2014. Adapted from Figure 2 in [9].

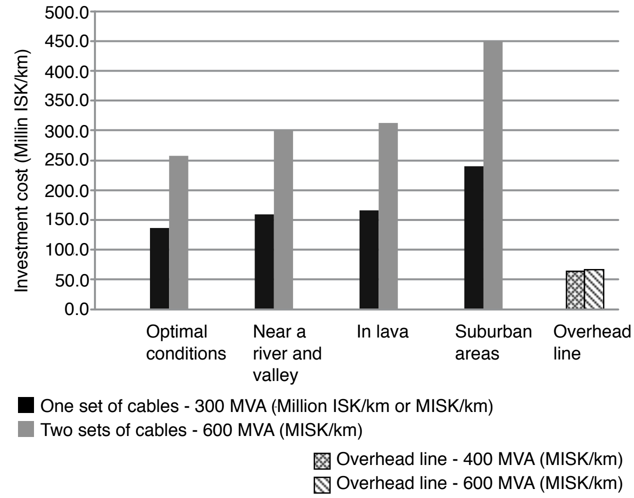

Figure 7. A comparison of cable and overhead line costs. The columns at left show costs for underground cable according to [4] while the rightmost columns show costs for comparable over-head lines. Adapted and translated from Figure 2.1 in [4].

the LTSP, however, are that the life-cycle cost is considerable higher for cables than for overhead lines, as has been expected. This is especially true for higher voltages and is based on comparable transmission capacity for both options.

The electrical characteristics are, of course, quite different for these two types of transmission options. For instance, the capacitance of cables is much higher than that of the overhead lines, and the cables, therefore generate much more reactive power. This reactive generation can cause problems in voltage control and stability. Therefore, we have a limiting factor in terms of cable length, proportional to total capacitance, unless reactive compensation is introduced to mitigate the undesirable effects of cable capacitance. By introducing coils with the appropriate reactance (inductance) at regular intervals, it is possible to neutralize the capacitance, but at a cost.

Also the heat conduction characteristics in the ground, around the cable itself, such as that of the earth and filling around the cable, influence the cable operating conditions and transmission capability. For instance, lava fields, which may be a common case for Iceland, are poor conductors of heat. Also the cost of moving the filling material, such as sand and gravel, may influence the life cycle costs greatly. However, with larger and thicker cables, it is possible to offset poor ground conditions in the cost of earth work and preparations.

Figure 7 shows the principal cost results in the comparison of these transmission options, according to [4]. With comparable transmission capacity of, for instance, 600 MVA the Figure shows that the cable option is approximately 4 to 8 times more costly than the over-head line option, since each km of an overhead line set costs around 60 MISK (Million Iceland krona), while the cost of cables with the same capacity may range from 250 MISK to 450 MISK. Note that the exchange rate for the Iceland krona (ISK) against a U.S. $ (dollar) is as of May 2016 around 120 ISK for 1 US$. This cost difference is quite heavy and would influence the decision, whether to replace overhead line options with a cable options, for instance across the sensitive highlands between zones N or NA and S. This will be discussed further in the next Section.

We now turn to discussing the major findings of the Landsnet policy paper [4], based on assumptions as set forth in Section II and elaborated in further detail below.

IV. Major results and conclusions

In this Section the major results are presented, based on [4] and other considerations.

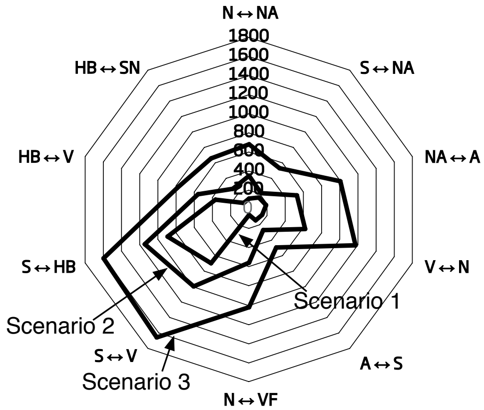

Figure 8. Transmission requirements between zones in MVA. The corner points show maximum transmission capacity to meet the load matching the Master Plan's (MP) generation in the utilization category for each corridor between zones. The transmission requirements are represented by closed curves, and expansions are then compared with the grey or shaded sectors in the diagram. Adapted from [4].

A. Main results and discussion

The principal results, as stated in the LTSP, show a general lack of transmission capacity, especially in rural areas. Some scenarios show that bottlenecks are already present or limits are approaching rapidly, such as in the south-west zones. The following corridors between zones most often showed transmission limits and hence will have to be reinforced: (See page 6 in [4]).

1) S ↔ NE
2) HS ↔ SN
3) NA ↔A
4) N ↔ NA
5) HS ↔ V

Figure 8 from [4] shows the main results of the LTSP in terms of the needed transmission capacity between zones, as represented in the LTSP. The diagram shows the major corridors as corner points, where a larger distance from the center indicates a high transmission need. The corner points show maximum transmission capacity to meet the load matching the Master Plan's generation in the utilization category. The transmission requirements are represented by closed polygons, and expansions are then compared with the grey or shaded sectors in the diagram.

A connection between the S zone and the north east parts of Iceland (N, NA and A zones) is necessary in all three scenarios in order to secure sufficient power flow between these parts.

The outer closed curves (Scenarios 2 and 3) show the transmission requirements from the utilization category (50% and 100%) but the innermost curve (Scenario 1) shows the basic requirements for the zero scenario, that is with no additional power. A probabilistic analysis on power shortage, during the planning horizon shows that a minimum of extra 70 MW installed capacity is needed, to keep the probability of power shortage within acceptable limits, if only the general load is considered, as discussed in the LTSP.

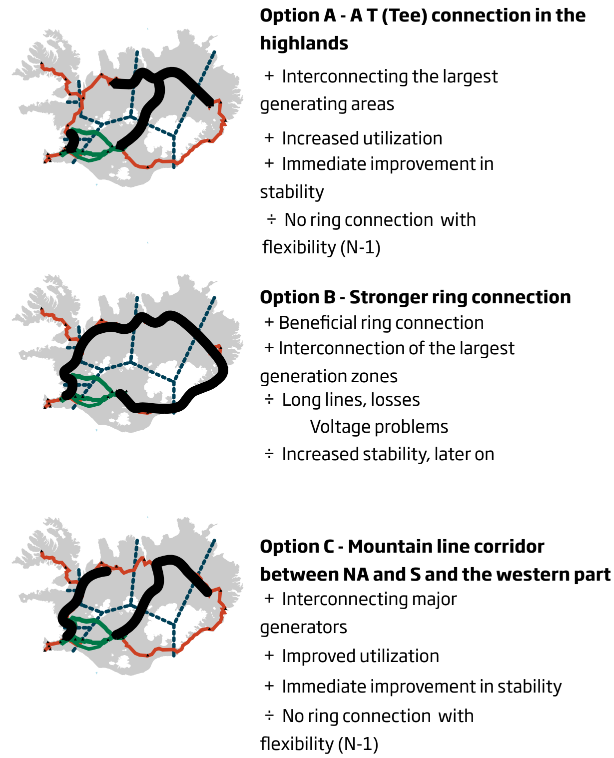

Figure 9. The Figure shows the three options resulting from matching load and generation. Each map shows the 8 zones and the main transmission corridors, with various configurations for reinforcement associated with the three options A, B and C, where in each case a short text description of the main features follows. The corridors to be strengthened are shown clearly with thick black solid lines in each case. Adapted from [4].

For instance the link between NA and A zones in Figure 8 shows that the transmission requirement is 200 MVA in the zero scenario. With 50% utilization in the Master Plan the requirements increase to approximately 550 MVA and with total utilization in Scenario 3 it will become 1000 MVA.

The corresponding figures for the link between zones S and NA are in the same order 170 MVA, 220 MVA and 550 MVA. The results are used to form three realistic options for the next ten years, where the transmission requirements should be satisfied and system stability and security simultaneously improved. Common to these option is that none of them satisfies completely the requirements associated with the utilization category of the Master Plan. We assume a ten year expansion pattern and with an expanded horizon, the transmission system needs to be further reinforced, if all projects of the MP utilization category are realized.

Figure 9 shows a sketch of these three options, with their associated principal pros and cons. The strengthening of the system with these options can be compared to the transmission requirement with the shaded sectors, as shown in Figure 10. The comparison is made with three different arrangements, in terms of different voltage levels and transmission capacity. By choosing a line with 623 MVA capacity, as shown with the dark sector, the transmission requirements are almost fulfilled. Also the transmission capacity with 132 kV lines

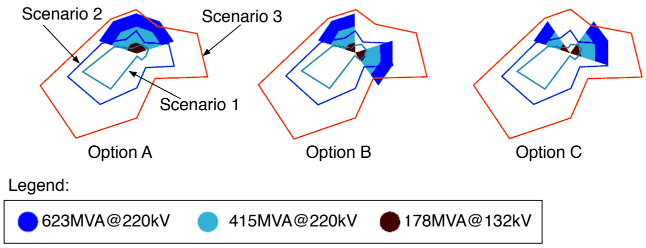

Figure 10. This figure is adapted from a figure on page 7 in [4] and is an extension to the results in Figure 8

(The innermost black sector), will fall short of transmitting the power according to the generation options in the Master Plan (MP) in the utilization category. A comparison was made of expanding the transmission system with 132 kV and 220 kV. The results show that new 132 kV lines are unrealistic as a part of the main transmission system, as indicated by the small black sectors in Figure 10. Their transmission capacity is very limited and many parallel lines are needed for transmitting the same power as a single 220 kV line. This also brings up the similar early results from [6] more than 30 years ago, where even then the results clearly indicated a flexibility and capacity using 220 kV lines instead of 132 kV lines, which at that time was primarily oriented towards the (then) new construction of the Southern line between zones S and A.

Furthermore, large capacitor banks are needed to keep the voltage within operating limits, The present transmission system will not meet the requirements of increased load according to the energy forecast. The present 220 kV lines need to be strengthened, especially in the scenario which assume all utilization from the Master Plan, since most of the lines have a transmission limit of approximately 300 MVA. In all cases the line between zones HB and V, on one hand and the lines between HB and SN zones, need to be strengthened. In some cases the line between HB and S needs to be strengthened, and this is possible by raising the voltage of present lines to 400 kV, when the need arises.

B. Some conclusions and comments

The main conclusions and comments regarding of the paper and its topic can be summarized as follows:

- The three options (or expansion configurations) in Figure 9 can all serve to mitigate the transmission bottlenecks in the horizon studied ranging up to 10 years from the date of the LTSP.
- No definite cost comparisons are given in LTSP for the three optional expansion configuration in the LTSP. However the LTSP discusses at length the underlying assumptions as aspects for each zone, which is however beyond the scope of this paper.
- An early study [6] showed that 220 kV would be more appropriate and economical for the Southern line, however the final decision was made at the time in the early 1980s to keep the voltage level at 132 kV.
- The conclusion of using 220 kV lines or even higher voltage levels is important with respect to a "highland line" or lines between zone S and the NA zone. It goes through the very sensitive highlands and is needed, as indicated in two out of the three optional expansions in Figure 9. There is a strong environmental movement against any line in this corridor and even strong public opinion against it due to the "visual pollution" it may cause in the highlands.
- One of the three optional expansion paths shown in Figure 9 indicates an upgrade to higher voltage levels for the "Southern line" as originally suggested in [6].

Acknowledgment

The author would like to thank the Rector of the University of Iceland (UI) and other key officials at UI for presenting an opportunity to write and present this paper.

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