Landsnet – 15026

HIGH VOLTAGE UNDERGROUND CABLES IN ICELAND

Research Project Concerning Options and Cost for 132 kV and 220 kV Underground Cables for Different System- and Ground Conditions General Discussion and Study of Three Different Cases

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GENERAL DISCUSSION AND STUDY OF THREE DIFFERENT CASES

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Information sheet – Options and Cost for Underground Cables in Iceland. Research Project					
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SUMMARY AND MAIN CONCLUSION

Objectives and scope

In 2014 a group of experts in the field of high voltage cable and cable installation from Iceland and Denmark worked with Landsnet in an extensive project concerning the installation of 132 kV and 220 kV underground cables in Iceland. The objective was to analyse and identify the most economic options in cable selection and installation in terms of transmission capacity, reliability, and cost.

The main tasks of the project were:

- To identify the most cost-effective selection/option of cable size, laying and sanding/casting for different capacities and conditions.
- To research and identify possibilities in reducing heat-resistance in cable filler material.
- To elaborate on different techniques in cable laying, experience in other countries and pros & cons for Iceland.
- To identify different possibilities in reducing cost by minimizing paths for vehicles, reducing joints etc.
- To evaluate investment and operational cost for cables for different ground conditions and various transmission capacities.

Along with a general study, three potential project-cases were examined separately:

Case I – Sprengisandur:
Partial undergrounding of a 220 kV (400 MVA) line in Sprengisandur. An evaluation of the maximum possible cable length, with respect to connections to existing transmission grid, was a part of the study.

Case II – Eyjafjörður:
A 12 km, 220 kV (600 MVA) cable in Eyjafjörður. Five variations were studied.

Case III – Hafnarfjörður:
A 1.5 km, 220 kV (300 MVA) cable in Hafnarfjörður. Two variations were studied.

General results

The study has shown that the location of individual cable projects in Iceland is on one hand affected by the technical restrains of the transmission system, and by site conditions on the other. The short circuit capacity varies greatly between the Southwest part of Iceland and the North. Furthermore, the weaker parts of the system feature very low short circuit values. This is most likely going to be the greatest physical restraint to limit potential cable lengths. Phenomena such as excessive voltage levels during low load conditions, and low resonance frequency values represent technical limits to cable lengths for each project.

Thermal dissipation of the soil surrounding underground cables affects the capacity of the cable. Thermal conditions in Icelandic soils are quite unfavourable. National average of thermal resistivity of in-situ soil is 1.5 K*m/W, while the average for borrow areas is 1.8 K*m/W. Values for resistivity of backfill material should not be estimated lower than 1.3 – 1.5 K*m/W, given favourable conditions. For comparison, thermal resistivity of 0.8 K*m/W is used as a reference value for Danish backfill material. Therefore the capacity of the same type of cable is around 30% higher in Denmark. It would be a great benefit if the thermal dissipation of the soil surrounding the cables could be improved. During work on the project, abundant waste quartz was located at Grundartangi in Hvalfjörður. It is considered viable to mix quartz with local sands on project sites, to use the quartz directly in some cases, depending on transport options, or for special solutions where thermal resistivity has a significant effect on the cable selection.

Different techniques of cable installation used by other countries where studied. The conclusion of this study was that in exceptional circumstances new methods could be useful, but installation in a traditional open trench is the most efficient and cost effective method in most cases in Iceland. Opportunities for increased efficiency in this respect are considered limited.

For cost comparison, an installation method used in recent cable projects in France was studied, where the cable was inside pipes installed in a narrow trench with a concrete cover. The cost of the French method was found to be non-competitive for typical site conditions in Iceland, compared with installations in basic cross-section with traditional backfill material. The installation cost was estimated to be up to 3.5 times higher without factoring in reduced cost in cable or other materials.

The possibility of using steel plates as a service road along the cable route instead of traditional gravel path was studied in the project. The result was that the cost of buying or renting and handling steel plates is higher than the cost of gravel path. However, if the gravel path needs to be removed after construction, the cost of using steel plates is comparable or lower. For project sites that are particularly vulnerable and require extensive access roads that need to be removed after the project is completed, the use of steel plates can be considered an option.

In the past few years the price of high voltage underground cables has been decreasing, especially for the largest cables in 220 kV and above. This is partly due to improved technology, but also due to competition in the cable manufacturing market where an increase in demand has been met with increased manufacturing capacity. Cost of cable jointing (material and assembly work) is a relevant cost, and failure rate is related to the number of joints. Therefore it is beneficial to increase length between joints, if roads and installation equipment are not a limiting factor regarding drum weight.

Installation cost (earthworks, cable laying and finishing) is a large part of the investment cost and it can vary significantly between projects, depending on site conditions and project requirements. The cost difference when installing one set of cable in an open trench can be up to triple between individual projects, depending on factors such as bedrock that needs to be removed in the cable route, access to suitable backfill material, special crossings, need for a service road, requirements regarding the removal of a service road post construction, requirements to remove extra material from excavations, and requirements on surface finishing after installation.

Installation of a single set of cable in an open trench can disturb a 10-14 m wide zone based on conditions and methods. It is very much depended on the type of land and how easy it is to restore previous surface. Most agricultural areas can easily be restored, but installations in a forested land, for example, will leave a tree-less zone over the cable. When installing a cable in lava, restoring the surface completely is not a possibility. Moreover, conditions in lava are not feasible for high voltage cables. Lava fields have, by definition, a certain protection status in the Icelandic conservation law. Cable installations in undisturbed lava should be avoided when possible.

Result of the case analyses

Sprengisandur

The total length of a transmission line between the southern part of the transmission system and the northern part across Sprengisandur is 200 km. The maximum possible cable length was studied in the evaluation. The weather can be very harsh in the area, which will, along with accessibility constraints, result in short working seasons. Geological conditions are rather favourable. Required transmission capacity in the case studied was 400 MVA, which requires one set of 2000 mm^2 Al cable. Results of the maximum cable length study, with respect to connections to existing transmission grid, was around 50 km, which would require compensation reactors at both cable ends. Estimated investment cost is around 133 Mkr/km.

Eyjafjörður

The total length of a proposed transmission line between Akureyri and Krafla is 90 km. Undergrounding of the first 12 km in Eyjafjörður was studied. The installation process is technically challenging. The cable route crosses two major rivers, a forest, an airport and a national conservation wet-land. Required transmission capacity in the base case studied is 600 MVA, which requires two sets of Al cable. The need for reactive compensation is not extensive Three options regarding routing were studied. In addition to the base case, two options with lower transmission capacities were studied. The estimated investment cost of two sets of Al cable is 204-240 MISK/km[1] depending on the chosen route. An alternative with one set of Cu cable, with one spare phase, was investigated. It was found not to be price competitive. The estimated investment cost of installing first one set of Al cable with half of the required transmission is 111.4 MISK/km for the most economic route.

Hafnarfjörður

The total length of proposed Suðurnesjalína 2 is 30 km. Undergrounding of 1.5 km in Hafnarfjörður was studied. The process is technically challenging due to installations in lava, considerable amount of utility crossings and major road crossings will be laid over the cable. The cable power transmission capacity studied is 300 MVA, which requires one set of Al-cable. There is no need for reactive compensation. The location of the project allows for the use of quarts sand as thermal backfill material, which in turn allows for the use of smaller and cheaper cables. Estimated investment cost 150-156.7 MISK/km depending on the cable size and backfill material.

The three cases differ in many respects, and the difference is reflected in the estimated unit cost [cost/km] for each case. The results show that a reliable cost estimation can only be established by studying and evaluating individual cases considering all relevant factors. Factors that had the largest effects on unit costs in these cases were: required transmission capacity, need for reactive compensation and site conditions on cable route, special crossings, and project size.

[1] Million ISK per km.

SAMANTEKT OG MEGIN NIÐURSTÖÐUR

Markmið og umfang

Árið 2014 vann verkefnishópur á vegum Landsnets, með sérfræðingum á sviði jarðstrengja og jarðstrengslagna frá Íslandi og Danmörku, að umfangsmiklu rannsóknarverkefni varðandi lagningu 132 kV og 220 kV háspennustrengja á Íslandi. Markmið verkefnisins var að greina hagkvæmustu kosti við val á jarðstrengjum, lagningu þeirra og frágangi með tilliti til flutningsgetu, kerfisaðstæðna, áreiðanleika, umhverfis og kostnaðar.

Megin verkefni hópsins voru:

- Fjalla um og skilgreina hagkvæmasta val á strenggerð, -þversniði, -lagningu og varmaleiðandi efni miðað við mismunandi flutningsgetu.
- Kanna möguleika á að lækka varmaviðnám í strengjasandi.
- Lýsa mismunandi aðferðum við lagningu jarðstrengja, reynslu annara fyrirtækja (erlendis) af þeim og greina kosti og galla fyrir mismunandi aðstæður á Íslendi.
- Fjalla um möguleika á að draga úr kostnaði við strenglagnir, s.s. með lágmörkun slóða og fækkun á tengingum.
- Leggja fram nýtt mat á kostnaði jarðstrengjaverkefna (stofnkostnaður og líftímakostnaður) við nokkrar skilgreindar aðstæður og flutningsgetu.

Samhliða almennri umfjöllun um jarðstrengi er í skýrslunni fjallað sérstaklega um þrjú tilvik:

Tilvik I – Sprengisandur:
Lagning hluta af 220 kV (400 MVA) Sprengisandslínu í streng. Hluti rannsóknarverkefnisins var að kanna hver hámarks lengd slíks strengs gæti verið, með tilliti til tengingar inn á núverandi flutningskerfi.

Tilvik II – Eyjafjörður:
220 kV 12 km löng strenglögn við Akureyri. Þar sem fimm valkostir voru skoðaðir.

Tilvik III – Hafnarfjörður:
220 kV 1,5 km löng strenglögn í Hafnarfirði fyrir 300 MVA flutningsgetu

Almennar niðurstöður

Undanfarin ár hefur verð jarðstrengja fyrir hærri spennur með mikla flutningsgetu lækkað mikið, eða um allt að helming fyrir stærstu 220 kV strengi miðað við aðgengileg gögn hvers tíma. Þó svo að á sama tíma hafi ýmsir aðrir kostnaðarliðir við jarðstrengjalagnir hækkað, hefur heildarstofnkostnaður við jarðstrengslagnir lækkað á hærri spennum, en gera má ráð fyrir að innkaupsverð á jarðstreng ásamt samtengingum sé um 30-50% af heildarstofnkostnaði við 220 kV jarðstrengslögn. Verð á minni strengjum fyrir lægri spennur hefur lækkað mun minna. Ástæður verðlækkunar á stærri strengjum eru taldar nokkrar, s.s. tækniþróun í framleiðslu strengja og þrátt fyrir mikinn vöxt í eftirspurn eftir strengjum hefur framboð aukist hraðar m.a. með vaxandi þátttöku framleiðenda utan Evrópu. Ljóst er að tiltækar eru áreiðanlegri upplýsingar í dag en fyrir nokkrum árum um verð á jarðstrengjum og stofnkostnað jarðstrengjaverkefna og upplýsingarnar verða áreiðanlegri eftir því sem verkefnum fjölgar.

Samtengingar strengja eru dýrar og algeng orsök bilana í strenglögnum. Því er mikið unnið með fækkun þeirra, sem þýðir að hámarka þarf lengd hvers strenghluta sem er á hverju kefli. Bæði vegir og tækjabúnaður eru takmarkandi þættir fyrir stærð og þyngd strengkefla.

Íslenska raforkukerfið er þeim annmörkum háð að skammhlaupsafl, sem er mælikvarði á styrk raforkukerfis, er lágt miðað við meginlandskerfi og að auki mjög mismunandi milli landshluta. Á Suður- og Suðvesturlandi er raforkukerfið til að mynda mun sterkara en á Norðurlandi. Skammhlaupsafl veikari hluta kerfisins mun í flestum tilvikum verða takmarkandi þáttur fyrir lengd jarðstrengja í kerfinu.

Skoðaðar voru mismunandi aðferðir sem nágrannaþjóðir okkar, sem eru framarlega í jarðstrengslögnum, beita við lagningu sinna strengja og kannað hvort hugsanlega mætti bæta aðferðafræði við strenglagnir hérlendis. Niðurstaða þessara athugana var m.a. sú að hefðbundin lagning strengs í opinn skurð er ódýrasta lagningaaðferðin í langflestum tilfellum og tækifæri til aukinnar hagkvæmni hvað það varðar því takmörkuð. Til samanburðar var m.a. skoðuð lagningaraðferð sem notuð hefur verið í nýlegum jarðstrengjaverkefnum í Suður-Frakklandi þar sem rör fyrir strengi eru steypt í þröngan skurð. Kostnaður við þá aðferð er metinn um 3,5 sinnum hærri en við hefðbundna aðferð. Við sérstakar aðstæður, svo sem þveranir, í votlendi eða þéttri byggð, geta aðrar lagningaaðferðir, sem lítt eru þekktar hérlendis, komið til greina.

Kostnaður við jarðvinnu, útdrátt strengja og frágang er umtalsverður hluti stofnkostnaðar og getur verið mjög breytilegur eftir aðstæðum. Þannig getur kostnaðarmunur verið allt að þrefaldur milli hagstæðra og óhagstæra skilyrða við þennan verkþátt, sé miðað við lagningu á einu strengsetti í opinn skurð.

Eiginleiki þeirra jarðefna, sem umlykja streng í skurði, til að leiða varma frá strengnum (varmaleiðni) skiptir miklu máli varðandi flutningsgetu hans. Almennt er jarðvegur á Íslandi með minni varmaleiðni en jarðvegur í nágrannalöndunum. Stafar það m.a. af háu hlutfalli eldfjallagjósku. Til samanburðar er varmaleiðni í fylliefnum á Íslandi úr sérvöldum námum allt að helmingi minni en almennt í jarðvegi í Danmörku sem þýðir að flutningsgeta á sömu stærð strengs er að öðru óbreyttu um 30% meiri í Danmörku. Þennan mismun er mikilvægt að hafa í huga þegar kostnaður jarðstrengslagna á Íslandi er borinn saman við lagnir í öðrum löndum. Mikill ávinningur er í því fólginn að bæta varmaleiðni fylliefnis. Kannaðir voru möguleikar á því að nota önnur efni, t.d. kvars sem fellur til við iðnaðarframleiðslu innanlands, til að auka varmaleiðni í fylliefnum með strengjum og eru niðurstöður jákvæðar.

Við leiðarval jarðstrengja er mikilvægt að leggja áherslu á lágmörkun umhverfisáhrifa. Að jafnaði má gera ráð fyrir að 8-14 m breitt svæði raskist í heildina við lagningu á einu 220 kV strengsetti. Auðvelt er að endurheimta fyrra yfirborð eftir lagningu strengs í sanda, vel gróið mólendi eða ræktarland. Liggi strengleið um skóg- eða kjarrlendi verður að skilja eftir skóglaust svæði yfir strengnum. Í hrauni eða þar sem klöpp liggur í yfirborði er ekki hægt að að koma yfirborði lands í fyrra horf. Nútímahraun njóta verndar skv. 37. gr. laga nr. 44/1999 um náttúruvernd, auk þess sem aðstæður í hrauni henta illa fyrir strenglagnir. Er því ástæða til þess að forðast strenglagnir í hrauni eins og kostur er.

Niðurstöður greiningar á tilvikum

Sprengisandur

Heildarlengd línu yfir Sprengisand er um 200 km og metið var hversu langan streng væri tæknilega mögulegt að leggja á Sprengisandi við núverandi kerfisaðstæður. Strengleiðin liggur um erfitt veðursvæði, með ófullkomnu vegakerfi. Jarðfræðilegar aðstæður til strenglagnar eru ágætar en stuttur mögulegur verktími ár hvert eykur kostnað. Gert var ráð fyrir 400 MVA flutningsgetu sem grunntilfelli sem þýðir að nægjanlegt er að leggja eitt sett af stærstu gerð álstrengs. Niðurstöður útreikninga gefa til kynna að hámarkslengd á streng í línu yfir Sprengisand sé um 50 km og eru það kerfislegir þættir sem eru takmarkandi. Strengur af þeirri lengd kallar á uppsetningu sérstaks búnaðar (útjöfnunarstöðva) við báða enda hans til að mögulegt sé að reka strenginn.

Áætlaður stofnkostnaður jarðstrengslagnar á hvern kílómetra á Sprengisandi er um 133 milljónir kr/km (eitt sett af 2000 mm^2 Al-streng).

Eyjafjörður

Heildarlengd áætlaðrar 220 kV línu milli Akureyrar og Kröflu er um 90 km og var lagning fyrstu 12 km línunnar framhjá Akureyri í jarðstreng skoðuð. Jarðstrengsleiðin liggur við þéttbýli, útivistarsvæði og flugvöll, þverar tvær stórar ár og votlendi. Lagning strengsins er því tæknilega nokkuð flókin. Skoðaðir voru þrír mismunandi valkostir varðandi leiðarval. Gert er ráð fyrir 600 MVA flutningsgetu sem grunntilfelli en það er áætluð flutningsþörf. Það þýðir að eitt sett af álstreng dugar ekki til að uppfylla flutningsþörf. Samt sem áður var kostnaður við að leggja aðeins eitt sett af sömu strenggerð áætlaður til samanburðar, en það getur verið valkostur að leggja fyrst aðeins eitt sett og fresta lagningu á öðru setti vegna hagkvæmnisjónarmiða.

Áætlaður stofnkostnaður jarðstrengslagnar á hvern kílómetra í Eyjafirði er á bilinu 204-240 milljónir kr/km (tvö sett af 1600 mm^2 Al-streng) eftir því hvaða leið er valin. Stofnkostnaður lagningar eins setts af Al-streng með helmingi minni flutningsgetu er áætlaður um 111,4 Mkr/km ódýrustu leiðina. Skoðaður var sá valkostur að leggja eitt sett af Cu-streng með einum auka leiðara. Sá valkostur reyndist ekki samkeppnishæfur í verði.

Hafnarfjörður
Heildarlengd áætlaðrar Suðurnesjalínu 2 er 30 km og var lagning 1,5 km innan Hafnarfjarðar skoðuð. Jarðstrengsleiðin liggur við þéttbýli í nútímahrauni og fyrirhugað er að byggja mislæg gatnamót yfir strenginn. Flutningsþörfin til framtíðar er metin 600 MVA en þróun álags og orkuframleiðslu ræður mestu um það hvenær þörf er á lagningu annars strengsetts til þess að ná þeirri flutningsgetu. Þar sem flutningskerfi raforku er mun sterkara á Suðvesturlandi en Norðurlandi er ekki talin þörf því að leggja annað strengsett af öryggisástæðum, þannig að í verkefninu var skoðuð lögn eins strengsetts með 300 MVA flutningsgetu.

Staðsetning strenglagnarinnar býður upp á þann möguleika að nota kvars sem fellur til sem iðnðaðarúrgangur á Grundartanga í Hvalfirði sem varmaleiðandi fylliefni. Sé það gert er hægt að nota minni og ódýrari streng en ef hefðbundinn strengjasandur er notaður.

Strengverkefnin þrjú sem skoðuð voru eru ólík er varðar marga þætti og endurspeglast það í áætluðu einingarverði jarðstrengslagnanna. Niðurstaðan sýnir að nauðsynlegt er að skoða vandlega hvert verkefni fyrir sig með tilliti til allra þátta til þess að fá áreiðanlegar kostnaðarupplýsingar. Þeir þættir sem mest áhrif hafa á einingarverð strenglagnar eru; flutningskrafa línunnar, þörf fyrir útjöfnun, aðstæður á strengleið og stærð verkefna.

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1 PROJECT DESCRIPTION

1.1 Introduction

In early 2014, Landsnet, which operates Iceland's electricity transmission grid, commenced a research project concerning 132 kV and 220 kV underground cables. The objective was to analyse and identify the most economic options in cable selection as well as installation in terms of transmission capacity, reliability and cost. The main tasks were to identify the most cost-effective solution regarding cable size, cable installation, and cable backfill material for different capacities and ground conditions. To meet the goals of the project, different techniques and experiences of other countries were inspected and their pros and cons studied in terms of Icelandic conditions.

In addition to carrying out a general study of underground cables, and in order to provide a firmer understanding and comparison of the physicals tasks of installing underground cables in Iceland, it was decided to explore three project-cases instead of only basing the research on generalised conditions. These cases were:

- Partial undergrounding of a 200 km 220 kV transmission line connecting the South and Northeast parts of Iceland across the highlands (Sprengisandur). Different lengths of undergrounding were studied to identify the most realistic and cost-effective length. Required transmission capacity is S_n = 400 MVA.
- Partial undergrounding of a 90 km long 220 kV transmission line between Akureyri and Krafla in North Iceland. The case of inserting a 12 km long cable from Kífsá substation in the town of Akureyri, across a woodland area, an airport, and a river, was analysed. Required transmission capacity is S_n = 600 MVA.
- Partial undergrounding of a 30 km long Suðurnesjalína 2. The case that was studied was the undergrounding of the first 1.5 km from Hamranes substation. This analysis involves installing cable in the lava fields in Hafnarfjörður. Required transmission capacity is S_n = 300 MVA.

It must, however, be noted that the cases studied in this research project are not detailed designs for individual cable projects, but a study of one or few possible variants in each case.

1.2 Participants

The participants in the project come from Landsnet, Energinet.dk (the Danish transmission system operator, TSO), Reykjavík University, three Icelandic engineering firms: Mannvit, Verkís and EFLA, and StellaCable, a private cable consultancy in Denmark.

1.3 Landsnet's Existing Transmission System

Landsnet owns and operates all major electricity transmission lines in Iceland. The transmission system, hereinafter referred to as "the grid", carries electricity from energy generation companies to utilities and power-intensive industries all around the country. The grid includes more than 3,000 km of transmission lines and about 70 substations and transformer stations. The bulk transmission system consists of power lines with voltages of 66 kV and higher and a number of 33 kV lines. The main national grid operates on 132 kV and 220 kV. In the south-western part of Iceland, three 400 kV transmission lines have been built and two in East Iceland. Transmission lines are either built as overhead lines (OHTL) or as underground cables. The vast majority of Landsnet's transmission lines are OHTL, less than 5% of the total transmission system is underground cables. In the absence of regulations or official guidelines, Landsnet has used the following criteria for deciding when underground cables are considered an option:

- Transmission lines at 66 kV; underground cable solutions are viewed as the equivalent of OHTL.
- Transmission lines at 132 kV; underground cable solutions are examined in or close to urban areas, where the transmission distances are short and where the project involves the connection of an individual customer to the transmission system.
- Transmission lines at 220 kV; underground cables have so far not been considered feasible due to high cost, except in exceptional circumstances and then only on shorter sections.

The majority of underground cables owned by Landsnet are 66 kV, only a few shorter cables are operated on the voltages of 132 kV and 220 kV. Table 1-1 summarizes the 132 kV and 220 kV underground cables operated by Landsnet. The length altogether is around 80 km.

Table 1-1. 132 kV and 220 kV underground cables owned by Landsnet[2].

Nominal voltage	Year of Commiss-ioning	Name of link	KKS	Route	Length [km]	Conductor	Isolation
132	1974	Korpulína 1	KO1	End at Korpa	0.25	Al	XLPE
132	1989	Hafnarfjörður 1	HF1	Stekkur-Öldugata	2	Al	XLPE
132	1990	Hnoðraholtslína 1		End at Hnoðraholt	0.53	Al	XLPE
132	1991	Suðurnesjalína 1	SN1	End at Hamranes	0.07	Al	XLPE
220	1998	Búrfellslína 3	BU3	End at Hamranes	0.08	Al	XLPE
132	1998	Nesjavallalína 1	NE1	Mosfellsheiði-Korpa	15	Al	XLPE
132	2005	Stuðlalína 1	SR1	Hryggstekkur-Stuðlar	17	Al	XLPE
132	2006	Rauðavatnslína 1	RV1	End at A12 (Rauðavatn)	1.5	Al	XLPE
132	2007	Hafnarfjörður 1	HF1	Hamranes-Stekkur	2.6	Al	XLPE
132	2007	Fljótdalslína 2	FL2	Fljótsdalur-Brattagerði	7.1	Al	XLPE
132	2007	Hnoðraholtslína 1		Hamranes-Ásfjall	1.6	Al	XLPE
132	2009	Rangárvallalína 2	RA2	Rangárvellir-Becromal	4.43	Al	XLPE
132	2010	Nesjavallalína 2	NE2	Geitháls-Nesjavellir	24.9	Al	XLPE
132	2013	Hafnarlína 1	HA1	Ægissíða-Höfn	1.5	Al	XLPE
	Total				**78.56**		

As table 1-1 shows, Landsnet has installed less than 100 m of 220 kV underground cables. Practical experience in design, installation, and operation of underground cables with higher voltage is therefore limited. Therefore Landsnet sought assistance for the research project from Energinet.dk and StellaCable, both of whom have extensive knowledge and experience in the design and installation of such cables.

[2] (Two power generating companies in Iceland, Landsvirkjun and Reykjavík Energy, have installed a few 220 kV underground cables, connecting power plants to the transmission grid. These cables, which are approximately 1 km in length each, are not included in the list).

1.4 Use of Underground Cables Worldwide

Over the last decades, power transmission networks across the globe have been developed based on the use of OHTL. Transmission underground cables systems have been available for many years, but their development has been limited by large capacitance and dielectric losses as well as a relatively low power rating compared to OHTL.

In the past years, the number of underground and submarine cables for power transmission has increased considerably. This is partly due to improved technology with new materials and a larger and more stable cable manufacturing market. However, facing a large increase in power demands and difficulties in installing new OHTL in Europe, it has become essential to consider the use of longer underground cable links. This is demonstrated by the increasing numbers of long AC cable projects that have been carried out in many countries during the past 20 years.

Table 1-2 below, with an overview of High Voltage and Extra High Voltage underground cables of the world was reported in 2007 (1).

Table 1-2. Overview of High Voltage and Extra High Voltage underground cables in 2007 (1).

Country	Location	Project name	kV	Conductor (mm2)	Conductor material	Insulation material	Circuits	Cores per phase	route length (km)		Date
Australia	Sydney	Sydney South to Sydney Central	330	1600	Cu	PPL/DDB	Single	1	28	Direct buried, ducts, tunnel	
Austria	Wienstrom	Wienstrom	380	1200	Cu	XLPE	Double	1	5.2	Direct buried & tunnels	2005
Belgium	Belgian coast	Koksijde - Slijkens	150	2000	Al	XLPE	Single	1	30	Direct buried	May-06
Belgium	East of	Tihange - Avernas	150	2000	Al	XLPE	Double	1	30	Direct buried	Nov-03
Denmark	Copenhagen	Metropolitan Power Project	400	1600	Cu	XLPE	Single	1	12.0, 9.0	Direct buried	1997
Denmark	Copenhagen	Metropolitan Power Project	400	1600	Cu	XLPE	Single	1	12.0	Direct buried	1999
Denmark	Jutland	Aarhus-Aalborg	400	1200	Al	XLPE	Single	2	2.5,4.5,7.5	Direct buried or duct	Aug-04
Denmark	Jutland	Karlsgårde-Blåvand	150	1200	AL	XLPE	Single	1	35.0	Direct buried	2001
Denmark	Jutland	Tinghøj - Haverslev	150	1200	AL	XLPE	Single	1	21.0	Direct buried	
Denmark	Jutland	Mesballe-Aastrup	150	800	Al	XLPE	Single	1	27.6	Direct buried or duct	2000
Denmark	Jutland	Trige-Aastrup	150	800	Al	XLPE	Single	1	27.7	Direct buried or duct	2000
Denmark	Lolland	Radsted - Vantore Str.	132	1200	Al	XLPE	Single	1	18.0	Direct buried + ducts	2002
Denmark	Lolland	Radsted-Rødby	132	630	Al	XLPE	Single	1	25.0	Direct buried + ducts	1999
France	Alpes-Maritimes	Antibes - Mougins	225	1200	Cu	HDPE	Double	1	11.3	Duct bank	1997
France	Brittany	Locmalo-Plouay	63	800	Al	XLPE		1	19	Ducts in soil	
France	Ile de France	Avenir - Sausset	225	1200	Cu	XLPE	Single	1	17.9	Duct bank, trough and t	2001
France	Loire-Atlantique	Chabossière - Montluc	63	400	Al	XLPE	Single	1	10.1	Duct bank	2003
France	Pyrénées-Atlantiques	Mouguerre - Tamos	225	1000	Al	HDPE	Single	1	9.4	Duct bank and trough	1996
Germany	Berlin	Berlin Diagonal	380	1600	Cu	XLPE	Double	1	6,3 and 5,2	Tunnel	1998 / 2000
Germany	Schleswig-Holstein	Lubeck - Siems	220	1200	Cu	XLPE	Double	1	10.2	Pipes,direct buried	2004
Germany		Goldisthal Pumped Storage	380	630	Cu	XLPE	Four	1	0.4	Tunnel	2002
Ireland	Dublin	Shellybanks	220	1600	Cu	XLPE	Single		14	Direct buried, river cros:	1997
Italy	Milan	Turbigo-Rho	380	2000	Cu	XLPE	Double	2	8.4	Direct buried	2006
Italy	Milan	Pioltello	220	1600	Al	XLPE	Double	1	3+3	Direct buried	2005
Japan	Chubu	Shinmeika-Tokai	275	9400	Al	GIL	Double	1	3.3	Tunnel	1998
Japan	Chubu	Kawagoe-Nishinagoya	275	2500	Cu	XLPE	Double	1	14.4	Tunnel	2002
Japan	Tokyo	Shinkeiyo-Toyosu	500	2500	Cu	XLPE	Double	1	39.8	Tunnel, Bridge	2000
Korea	Inchon	Sinbupoung-Seoinchon	345	2000	Cu	PPL	Single	1	17	Tunnel	2002
Korea	Inchon	Sinbupoung-Seoinchon	345	2000	Cu	PPL	Single	1	17	Tunnel	2002

Today the demand to connect renewable energy sources to the grid or supply power to major infrastructure in remote locations has been increasing. In most countries the process of getting environmental approvals to build an OHTL can take as many as 7 – 8 years, whereas the process of getting approval for installation of underground cables in public areas may only take 1-2 years. The net result is that an AC cable link may be built in 2-3 years compared with 8 -10 years for an OHTL. This alone can be the reason to justify the AC cable link as it provides a much quicker return on the investment.

In Denmark, power generation has changed significantly due to its location as a transit country of energy between main Europe and the hydro power of Northern Europe, as well as the large increase in offshore wind farms and local renewable energy production. Denmark needed therefore an overall change in strategy for the reinforcement of the country's transmission network, which was approved by a majority of the Danish parliament. In 2007 the Energy- and Transport Minister established the Electricity Infrastructure Committee in order to make a technical report for the future reinforcements of the Danish transmission network (2).

In 2009, based on the Committee's conclusions, the Danish government took the first step worldwide towards a cable based transmission system. Due to the strategic location of the Danish grid, being a transit country between central and northern Europe, the strength of the

Danish grid network, and the fundamental change of the Danish power system with increased scattered wind power, it was possible to exchange the existing OHTL system for Underground cables. There was a choice between 6 different solutions, ranging from undergrounding the entire transmission system on 132-400 kV, to doing no grid expansion. The last solution was more of a common ground for comparison, as this option was not possible due to the age of the transmission system and fundamental changes in power generation in Denmark. After performing an independent analysis of these 6 possibilities, the Danish government, with the involvement of all stakeholders, chose a solution called option C with an estimated cost of 2.3 billion euro (3):

> *New power lines on 400 kV will be underground, while existing towers can be refurbished and new towers and overhead lines are to be chosen for an existing line route. There is to be improvement of the visual appearance of the existing 400 kV network, with new tower design and partial undergrounding on specifically chosen sections. The entire existing 132 kV and 150 kV grids are to be undergrounded.*

Following this decision, and due to the increase in the renewable offshore energy industry, many other countries are starting to increase their amount of underground cables. Therefore much work has now been done internationally in order to solve some of the technical problems with a large underground network.

For most HV/EHV AC cables additional "Inductive Reactance" e.g. "Reactor banks" are required at one or both ends of the AC cable link or in some cases at points along the line. For these, there are system issues which may need to be considered in respect to the influence on the transmission grid. Overall, there are many technical performance issues in respect to either a uniform HV or EHV AC insulated cable circuit or a hybrid circuit, e.g. one where the link includes both cables and overhead lines. A CIGRE working Group C4.502 has prepared a very comprehensive technical brochure: *"Power system technical performance issues relating to the application of long HVAC cables"* (4). This document describes many of the technical aspects that need to be considered in regard to the system design.

Whilst the system design is an essential feature of a long length AC link using insulated cables, there are many other practical issues that must be addressed. These issues are being analysed by the CIGRE working group B1.47 "Implementation of Long AC HV & EHV Cable Systems", to be finished in 2016.

As many of the technical problems mentioned here above are being investigated locally, it was recently reported by RTE[3] that there are no real technical gaps in the system yet. However, RTE states that the costs of HV/EHV underground cables still remain much higher than for OHTL, and that with the increased use of underground cables, their social acceptance also decreases. This is especially the case in rural areas, where farmers often prefer OHTL to underground cables (5). Nevertheless, the amount of underground cables is increasing, and the most recent reports from CIGRE WG B1.47 (June 2014) show 45 new cable projects worldwide meeting the Working Groups criteria for long AC cable lines[4].

[3] RTE, Réseau de transport d'électricité, is the transmission system operator in France. As Landsnet in Iceland, RTE is the owner of, and responsible for the transmission systems in France and has been actively enlarging its cable network in the past 5 years.

[4] In the draft version of WG B1.47, long AC cable lines are defined as AC cable lines where the load due to the capacitive current needs to be taken into account in the system design. Typically in central Europe, this would be 40 km for voltages less than 220 kV and 20 km for 220 kV or greater.

2 UNDERGROUND CABLES

2.1 Design of Cables and Cable Systems

This chapter gives a brief overview of underground cable design for the voltage levels under consideration, i.e. nominal voltage U_n = 132 kV and 220 kV. The respective highest voltages as defined in CENELEC/IEC standards are U_m = 145 kV and 245 kV. For these voltage levels, only single phase cables are available for underground cable applications. However, three phase versions may be applied for special applications as well as for submarine cable applications. These special cables are in fact three single phase cables, "packed" together in one common armour and outer jacket.

The main items of a typical single phase cable are shown in figure 2-1 below:

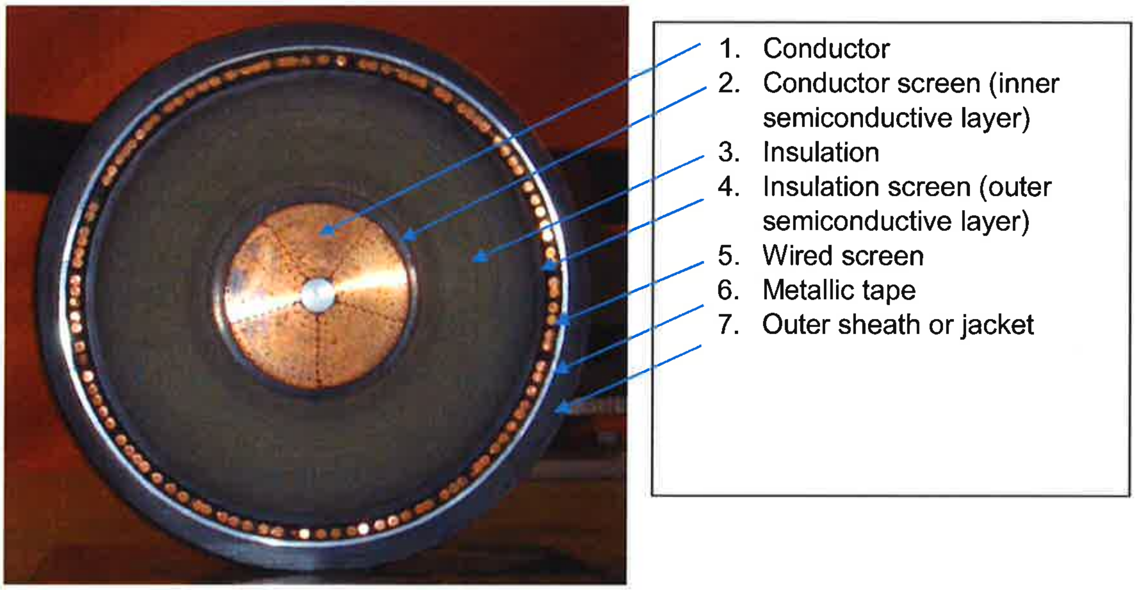


Figure 2-1. Example of a 220 kV cable with high power rating.

The cable shown in figure 2-1 is intended for very high current rating, with a segmental ("milliken") copper conductor. The main items shown on the picture are as follows:

1. Conductor. The purpose of the conductor is to provide a conductive path for the electrical current being transmitted through the power cable. Two materials and various designs are available, the most common type in the Scandinavian countries being round stranded aluminium conductors. In some applications, the free space between the conductor wires is filled with water swelling powder to limit longitudinal penetration of water in the event of water ingression. Current rating can – for the same cross sectional conductor area - be improved by the use of copper instead of aluminium as conductor material or/and by using alternative conductor patterns to reduce proximity- and skin effect, like the segmental pattern shown in figure 2-1. This pattern is used only for very large cross sections, at least 1000 mm2. Other conductor designs do exist but are not very common for HV cables, e.g. round solid conductors and hollow conductors.

2. Conductor screen. The conductor screen is made of a semiconductive material, sometimes along with swelling tape for prevention of water intrusion into the conductor. The purpose of the semiconductive material is electrically to limit concentration of the electrical field across the conductor surface and mechanically

to prevent any micro misalignments in the core wires from penetrating into the insulation layer.

3. Insulation. The insulation material of modern high voltage cables for AC applications is cross-linked polyethylene, abbreviated XLPE. XLPE is a material with a very high electrical resistance value, as well as other desirable qualities such as flexibility and durability. It is also easy to repair, at least compared to its most successful predecessor, oil-impregnated paper. XLPE is categorized with respect to cleanliness, e.g. clean, superclean or ultraclean where the cleanest materials are required for the highest voltages.

4. Insulation screen. The insulation screen is similar to the conductor screen and serves the same purpose. It is often extruded and bonded with the insulation but also sometimes furnished as a swelling tape for prevention of water intrusion into the insulation material. The outer surface is sometimes furnished with a layer of soft binder material for the wired screen.

5. Wired screen. This layer is made of wires that are arranged in a helical configuration, with one or more counter-helixes made of flat tapes of identical material. The material is copper for most cables. In recent years, many power companies have changed the preference from the traditional wired copper screen to aluminium foil. The purpose of the wired screen is to provide a Faraday cage around the energized conductor and thus to eliminate the electric field outside the cable, as well as to provide a return path for the capacitive charging current of the cable. The screen also serves to equalize dielectric stress around the insulation. In the event of insulation failure, the screen will provide a conducting path for the short circuit current to ground. The cross section of the copper screen is selected with respect to the short circuit current requirements in each application. The current in the conductors will induce voltage in the individual screens along the cable route. Depending on the conductor's current strength and cable length, the ways to manage these voltages must be carefully considered. The possible screen bonding methods are three: direct grounding of both ends; direct grounding of one end; and terminating the other end with a sheath voltage limiter or finally for longer cable lengths to limit the induced voltage by cross bonding of the screens across the three phases at regular intervals.

6. Metallic tape. In most cables, a layer of metal tape is required for improved resistance against radial water ingression. As described for the wired screen above, this layer may not be required if an aluminium foil or laminate is used instead of a wired screen. In the case of submarine cables, a continuous lead sheath is generally used for this purpose. This does, however, mean that the cable weight is increased significantly and the toxic properties of lead must also be taken into consideration. The purpose of this layer is to minimize the ingression of water into the insulation system. Water swelling tape and/or powder is typically applied under this layer, to limit the longitudinal progressing of water that might pass the metallic tape and thus to limit the amount of cable that needs to be repaired.

7. Outer sheath or jacket. The purpose of this layer is to provide mechanical strength and resistance against the surrounding environment, humidity and corrosion. Electrically, the outer sheath serves to provide insulation of the wired screen from ground. The most suitable material for this purpose for use in underground cables is high density polyethylene, abbreviated HDPE. To verify the integrity of the outer sheath by means of applying voltage between the wired screen and the sheath surface, a semi-conducting layer is often applied to the outer surface of this sheath.

This layer is made of semi-conducting polymer that is co-extruded with the outer jacket.

Many design variants for underground cables may be considered to adapt to individual requirements. For example, if outer mechanical stress is possible, cables may be furnished with steel armouring for improved strength. This is, however, mostly applied to submarine cables or very long sections with Horizontal Directional Drilling (HDD). In some applications a fibre optic (FO) cable is integrated into the power cable, e.g. within the wired screen. This FO cable may serve for monitoring of the operational temperature within the cable as well as for communication purposes, e.g. for control- and protection systems.

All the considerations above show that quite many design alternatives for each individual application need to be examined during the design phase. These alternatives need to be addressed, in context with the system requirements that the cable is intended to serve, the environmental conditions, selection of laying depth and backfill material, and other important factors.

Regarding the selection of cable type for each individual project, the first prerequisite is the required apparent power rating (or MVA rating) of the transmission line/cable. This is derived from system studies, based on the present network and load, as well as load forecast. Other design aspects will be derived from this basic prerequisite as well as items such as cable length, short circuit levels etc.

2.2 Cable Formations and Earthing Wires

In a three phase circuit, the cables can be placed in different formations. The most usual formations in Europe are trefoil (or triangular) formation and flat formation, as illustrated in figure 2-2.

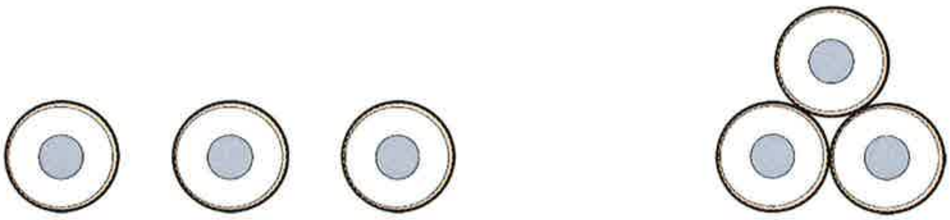


Figure 2-2. Flat formation (left) – trefoil formation (right)

In trefoil formation the cables are in close contact with each other, whereas in flat formation the distance between the cables can be adjusted.

2.2.1 Trefoil Formation

In the trefoil formation the cables for the three phases are laid as close to each other as possible to minimise the reactance (i.e. the reactive impedance) of the cable section. The cables are often bonded together to ensure that the formation will not be deformed. By arranging the cables in this way it is possible to minimise the current induced in the cable's metallic sheath. The strength of the magnetic field, which occurs above the cable due to the current flowing in it, is considerably lower than with flat formation. The trench required is narrower for trefoil formation than for flat formation. The trefoil formation is thus more suitable for urban areas.

Dissipation of heat from the phase conductors may however be problematic with this formation. The conductors are in close contact, thus the heat from one conductor will influence the heat development in the other two conductors. This will of course reduce the current carrying capacity. Trefoil formation thus generally requires cables with a larger cross sectional area of the phase conductor (and thus more expensive) than the flat formation, for the same current carrying capacity.

To reduce the impact of this heat exchange between phase conductors, it is possible to increase the distance between the cables in the trefoil formation. However, it may be difficult to maintain it over the whole cable length unless a concrete box with prefabricated holes is used. Increasing the distance between the conductors also increases the reactance.

2.2.2 Flat Formation

In this formation, the three phase conductors are arranged side by side in a horizontal plane with a fixed distance between them. The distance between the conductors leads to less heat exchange between the conductors than experienced with the trefoil formation.

If the metallic sheath is bonded in both ends, the current induced in it may have a negative impact on the current carrying capacity of the cable, i.e. by reducing it. To counteract this, a single-bonding approach may be applied, i.e. bonding one end with the other end open (but connected to ground through a sheath voltage limiter, SVL). Due to high induced voltage at the open end for longer distances, this approach is only applicable for shorter distances. For longer distances, cross-bonding of the metallic sheath must be applied. By cross-bonding the sheath the induced current can be significantly reduced (ideally eliminated), thus utilising the better heat dissipation properties obtained by placing the conductors at some distance apart. This formation is thus usually preferred for longer distances in rural areas.

If a continuous earthing wire (often referred to as "Earth Continuity Conductor" or simply "ECC") is laid along with cables on long routes in flat formations, care must be taken to maintain symmetry in the system by shifting the location of the wire along the route between every two joints. To achieve symmetry, the wire location should be at approximately 30% of the spacing between left and centre phase (closer to the left phase) for half the distance and then shifted to 30% of the spacing between right and centre phase (closer to the right phase) for half the distance. Figure 2-1 shows a brief schematic of the described arrangement.

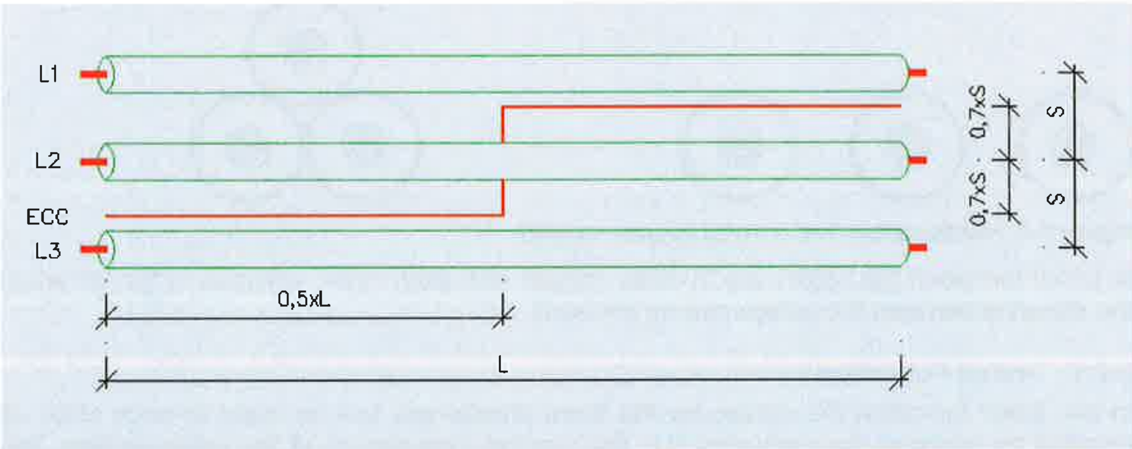


Figure 2-3. Arrangement of ECC for a cable route in flat formation

2.2.3 Magnetic Fields

The size of the magnetic field around underground cables depends on the layout of the cables, the laying depth in ground, and the actual current in the cable. When laying cables in a small area of urban environment, the tight trefoil layout is normally chosen. This is not only due to the available spacing, but also in order to minimize the magnetic field within cities. An example of the magnetic field around a cable system with a mean yearly current of 100 A is shown in figure 2-4.

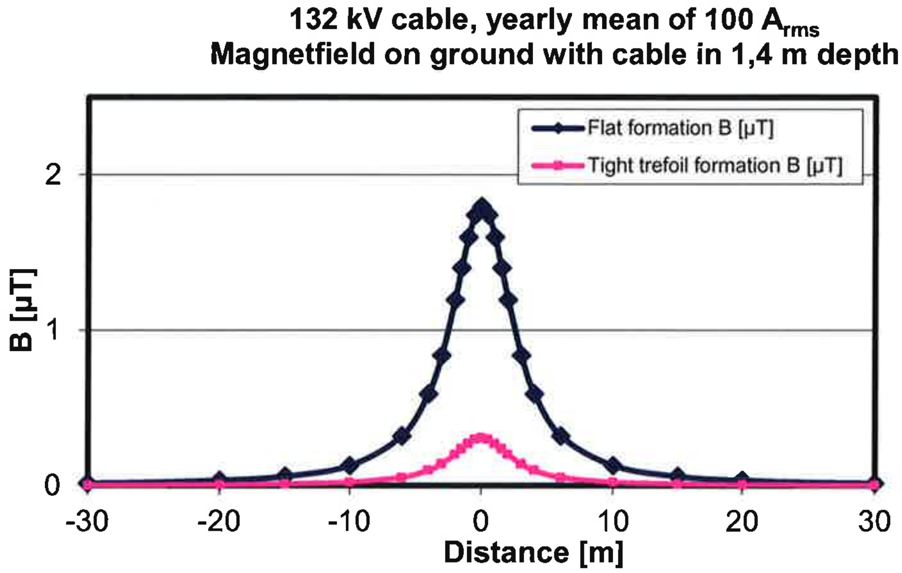


Figure 2-4. Comparison of the magnetic field around 132 kV cables laid in flat formation and tight trefoil formation. This typical example has a yearly mean current of 100 A_{rms}.

2.2.4 Earthing Wires

No general design rule regarding earthing wires will be stated in this report, as it is proposed that the necessity of implementing a continuous earthing wire along cable routes will be studied specifically for each project. Various studies and recommendations have been published on the matter, including the Cigré TB 283 (6) and TB 347 (7). Although every project must be considered specially, it can be stated that for most cases, these publications recommend the implementation of what is referred to as "ECC" (Earth Continuity Conductor) where cables are connected to an OHTL. It can also be stated that for most cases of cross-bound cable systems connected to substations, the same publications state that an ECC can be omitted.

However, in Icelandic conditions with relatively high ground resistivity, it is proposed that an earthing wire be laid alongside the cables in the trench bottom, at least for the first 0.5 km from each earthing point (including link boxes). This is for the purpose of connecting and making the wire an integral part of the local grounding system. The wire will assist in lowering the earthing ground resistance at each point and will in turn lower the local EPR ("Earth Potential Rise"). The local grounding system of each earthing point must be studied specially for each point, fulfilling the requirements set forth in standard ÍST EN 50522, *Earthing of power installations exceeding 1 kV a.c* (8).

For the three cases presented in this report, it is assumed that the cables will in all cases be connected to substations. For the Sprengisandur case, which is actually a "siphon" system, i.e. a partially undergrounded system, with OHTL on both sides of the cable section, the building at the cable end is considered equivalent to a substation, i.e. with a proper earthing system. As stated above, this assumption will be subject to separate system studies for each case at a later stage.

For the purpose of simplification of cost estimates in this report, it is proposed that approximately 25% of all cable routes will include an earthing wire (ECC).

2.2.5 Induced Voltage in Parallel Metallic Pipes

For long parallel lengths of metallic pipes and HV cables, there may be issues with induced voltages. If the pipes are grounded directly, then a small continuous asymmetric current in the cable system can induce circular currents on the pipe surface and ground. These circular currents can cause corrosion and break down of the metal pipe. In order to shorten the parallel distance, pipes are often split with insulated flanges at every connection point. However, if there is a fault on the cable causing earth potential rise in the area or induced voltages on one or more of the pipe sections, then a large voltage difference can occur over the insulated flanges. These pipes must therefore include a sphere gap or an SVL between pipe sections in order to control the voltage difference between pipe sections.

If the short circuit current is high, a high induced voltage can occur on a pipe running parallel to an HV cable. These voltages can become much higher than allowed touch voltages, and can be dangerous for persons working on the pipes. It is therefore essential that the cable system and parallel pipes are designed to minimize the induced voltages, or to ensure appropriate working procedures for work on pipes. The touch voltages should always be below the level shown in figure 2-5 (8).

It is important that the utilities for HV cables and pipes have a common understanding of work procedures and split of cost for securing a safe work environment and low touch potentials on both cables and pipes.

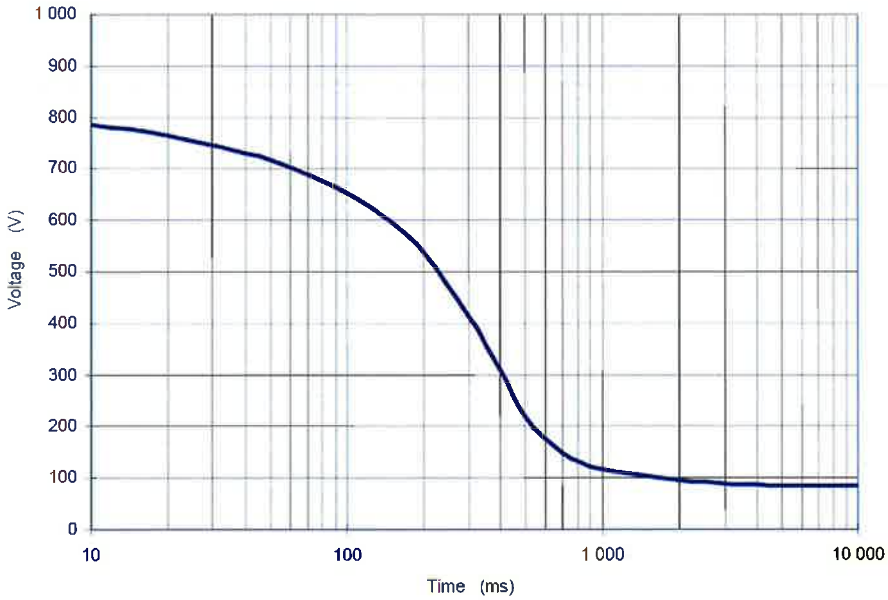


Figure 2-5. Allowed touch voltages as a function of fault time, from (8). For a fault duration of 100 ms, the maximum touch voltage is 650 V, while for a fault duration of 150 ms the maximum touch voltage is app. 150 V. For normal operation, the maximum touch voltage is normally defined as 50 V.

2.3 Ampacity Calculations

For estimating the minimum cable size, the steady state cable ampacity calculations for a required cable MVA rating are usually based on standard methods as described in IEC 60287. Using this standard the current rating can be calculated according to the following equation:

Equation 2-1

$$I = \sqrt{\frac{\Delta\Phi - W_d\,[0.5\,T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}}$$

Where:

$\Delta\Phi$ is the conductor temperature rise above the ambient temperature.

W_d is the dielectric losses.

T_1, T_2, T_3 and T_4 are the thermal resistances of the cable system and cable surroundings.

λ_1 and λ_2 are the sheath loss factors.

n is the number of current carrying conductors.

R is the conductor AC − resistance.

In this equation the unknown parameter is either the conductor current I or the operating temperature of the conductor. The normal procedure is to specify the conductor maximum operating temperature and then calculate the maximum conductor current in order to find the MVA rating of the cable.

The maximum operation conductor temperature for AC, XLPE cables is usually defined as 90°C but it is also a well known practise to calculate the cable rating based on lower conductor maximum operating temperatures in order to prevent the condition of the soil material surrounding the cable during operation drying out. The limiting factor with respect to drying out of soil is the outer sheath temperature. Traditionally, the critical value has been set to 50°C, but in a Danish PhD-Thesis (9) it is suggested that the critical temperature, i.e. when moisture migration may be expected to start, is closer to 60°C, at least for the sandy soils studied in that particular thesis. It is also concluded that higher temperatures can be allowed for shorter time periods without risking dry-out. The soil itself plays an important role and has to be assessed for each project. Drying out can be a problem as the heat transfer capabilities of the soil is lowered, giving rise to an increased insulation and even higher cable temperatures. The value of 60°C has been adopted by the French transmission company RTE as a value for the winter time but 55°C during summer time. The maximum allowed conductor temperature, for continuous operation, is generally 90°C according to manufacturers. To avoid drying out the surrounding soil, the maximum temperature on the outside of the outer sheath, referred to Icelandic conditions, is not to exceed 50°C for continuous operation. Thus, the risk of the soil drying out and the potential hazard of thermal runaway of the cable surroundings and consequent potential damage of the cable, will be limited.

It is also of importance to distinguish between operating modes of the cable. Continuous operation at a fairly steady flow puts more stringent requirements on the allowed temperature than cyclic operation. The Danish TSO, Energinet.dk, for instance has different criteria for cables in the main grid and cables transmitting for instance power from generating units into the main grid. For cables in continuous operation, the outer sheath maximum temperature is 50°C with allowed temperature rise to 60°C for a period of less than 40 hours. Emergency loading of up to 105°C on the cable conductor for shorter periods is also considered acceptable by cable manufacturers. Thus, if the main purpose of the cable is cyclic transmission (e.g. transmit power from a wind farm to the grid), the transmission capacity of the cable is considerably higher than if it is to be used for continuous, steady transmission.

In general, the transmission capacity of an underground cable is mainly determined by the heat produced by the current in the conductor and the ability of the material surrounding the cable (thermal backfill and native soil), to dissipate this heat. Therefore, the transmission capacity is often referred to as the thermal rating of the cable. When discussing thermal ratings of different cable circuits it is important to further define how the cable is operated, since there are a number of different thermal ratings, depending on the operation characteristics of the circuit. According to classification by CIGRÉ, of report 338 (10), the thermal ratings should be classified into four categories:

- **Nominal rating** or continuous rating, which is the most commonly used rating. By this rating it is assumed that the loading is continuous and the nominal rating is the maximum continuous ampacity under specific steady state circumstances.
- **Cyclic rating** assumes that the loading varies on a regular basis, giving the cable time to "cool off" between peak loading. Thus, the cable can be operated at higher temperature than when referring to nominal rating.
- **Short-term rating** is the ability of the cable to carry a relatively high load for a short time period, without exceeding the design temperature.
- **Real-time rating** is the maximum loading right now, with respect to the present conditions (soil temperature and humidity, preloading etc.). This is often referred to as "dynamic rating".

The cable circuit sections dealt with in this report are all located within the central grid, thus the nominal rating has to be applied.

2.3.1 Conductor Material and Conductor Design

As described in chapter 2.1, the conductor materials for underground AC cables are typically either aluminium or copper. The resistance of the conductor depends on the cross section of the conductor and selected material, but also on the conductor design where segmental conductor types are more commonly applied in the case of large conductors, in order to minimize losses due to proximity- and skin effect. The selection of conductor or suitable AC conductor resistance "R" for the cable system not only depends on the material selected, where the copper has lower resistivity, but also on the cross section and type of the conductor.

The cable cross section for 132 kV and 220 kV are more or less standardised to the following values in Europe, where cables sizes start at 300 mm^2 and are available in 400 mm^2, 500 mm^2 630 mm^2, 800 mm^2, 1000 mm^2, 1200 mm^2, 1400 mm^2, 1600 mm^2, and 2000 mm^2. The number of manufacturers who offer cables with 2500 mm^2 cross section is increasing but this size is used only in very special cases due to the increased weight affecting the installation process and the overall cost.

Figure 2-7 shows typical values, calculated from current ratings and rating factors in table forms (11), for 220 kV underground cable ratings and how these values are depending on conductor cross section from 400 mm^2 up to 2000 mm^2. Both aluminium (Al) and copper conductors (Cu) are shown. Cu conductors 1200 mm^2 and above are of segmental type. The values shown in the figure are based on fixed values of ambient temperature of 10°C, thermal resistivity of 1.5 K*m/W and screen of 95 mm^2 Cu. Figure 2-6 shows the physical arrangement and surroundings that are the basis for the values, i.e. a laying depth of 1.1 m. It is also assumed that the cable system is operated in continuous operation at maximum conductor temperature of 65°C, is installed in flat formation with (120+D) mm between cable centres and the cable screens are cross bonded.

Although the continuous current ratings shown in figure 2-7 are derived from "empirical" tables for a brief overview, the more detailed current ratings of each individual case study in this report, as described in chapter 5, 5.4 and 5.6, are calculated numerically with the aid of the application software Paladin DesignBase, where the geometrical arrangement is modelled along with the cable itself, backfill material, native soil and other factors.

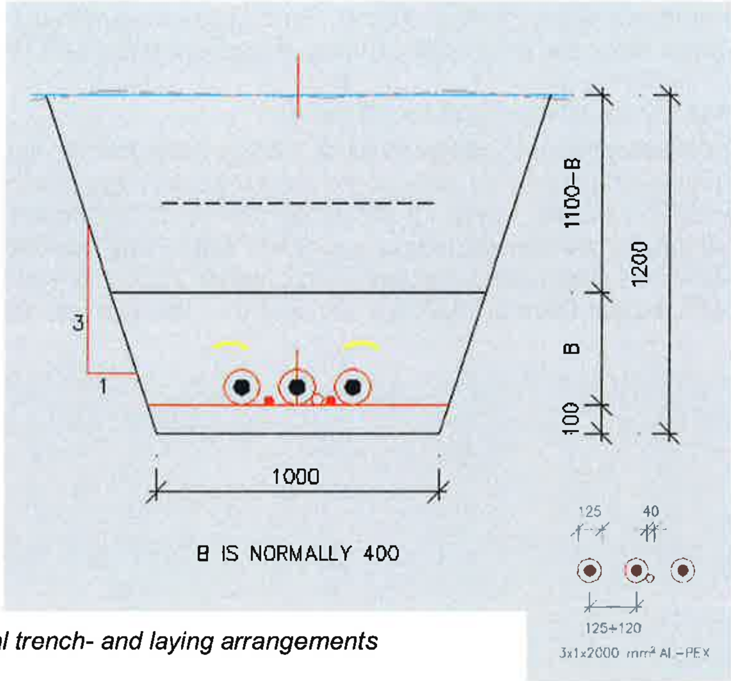


Figure 2-6. Typical trench- and laying arrangements

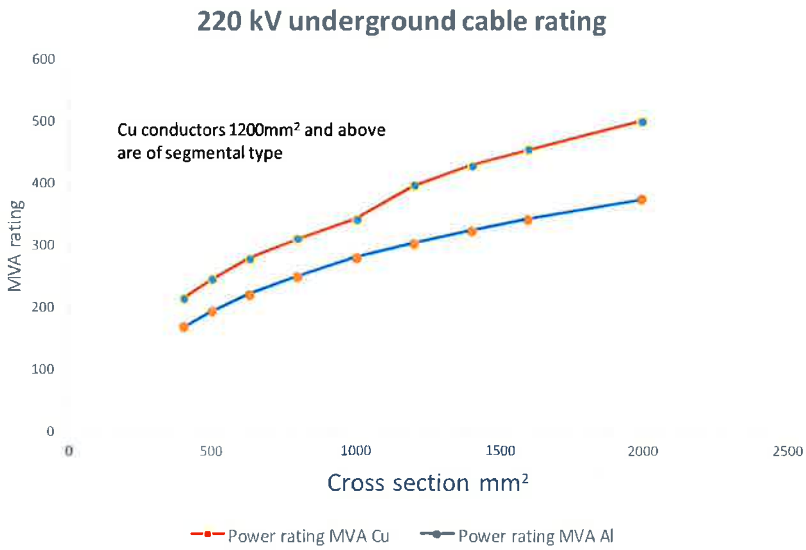


Figure 2-7. 220 kV Underground cable continuous current rating.

According to these values, the maximum 220 kV cable rating for 2000 mm^2 cable with an aluminium conductor is approximately 373 MVA, and approximately 500 MVA for a Cu conductor. These values may slightly differ between manufacturers due to difference in cable design e.g. stranded or segmented conductor used, insulation thickness, installation conditions etc.

If the required MVA rating of the transmission cable is, for example, above 600 MVA for the ambient temperature and thermal resistivity conditions given above, it is necessary to install two cable sets of either 1400 mm^2 Al cables or 800 mm^2 Cu cables where market prices of copper and aluminium will affect the final choice. For this case a single set of 2500 mm^2 Cu cables is not an option since the estimated capacity is approximately 546 MVA.

2.3.2 Thermal resistivity and ground temperature

Whereas figure 2-6 shows the main dimensions of a basic cable trench, figure 2-8 shows an explanation of the main items involved. One of the most important items is the thermal backfill material, surrounding the closest vicinity of the cable. This is of vital importance for Iceland, where very high values for the thermal resistance of the "native soil" surrounding the thermal backfill must be expected (see further discussion in chapter 3.10). For such surroundings, a thermal backfill with better thermal qualities will improve the current rating of the cable considerably.

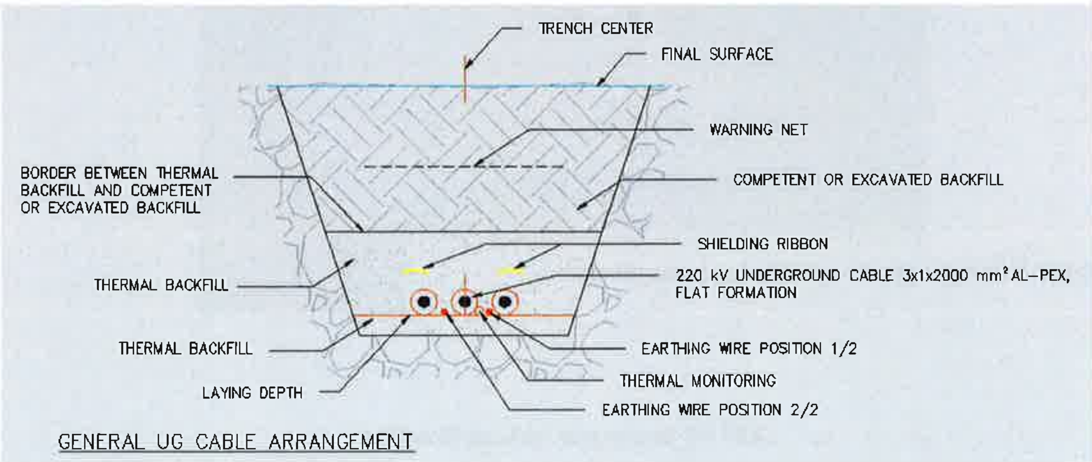


Figure 2-8. Explanation of cable trench items

Therefore, assessment of available backfill materials is important when selecting optimal conductor size during the design of a cable system. The following figure (figure 2-9 and figure 2-10) shows how the 220 kV underground Al cable rating of 1400 mm^2 varies with soil resistivity for the conditions described above.

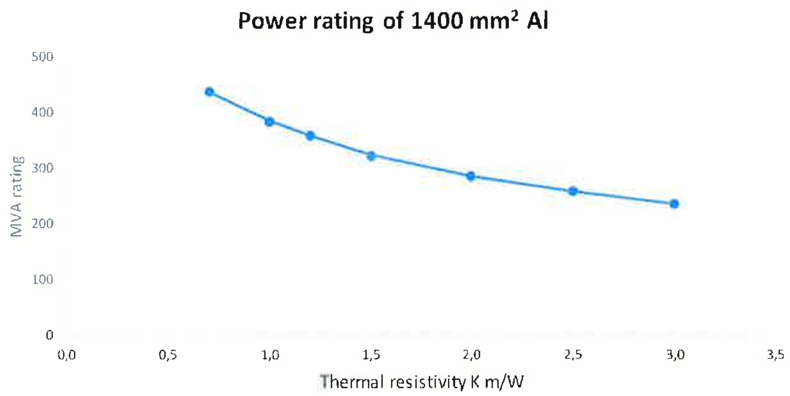


Figure 2-9. Power rating for a 220 kV cable system with a 1400 mm^2 Al cable conductors.

In case of soil resistivity of 1.5 K*m/W, the calculated rating of the cable is approximately 323 MVA but decreases to 235 MVA when the soil resistivity increases to 3 K*m/W, which means that the MVA rating is 27% lower. In case of lower soil resistivity of 0.7 K*m/W the rating of the cable is 438 MVA or 36% higher than the cable MVA rating at the soil resistivity of 1.5 K*m/W.

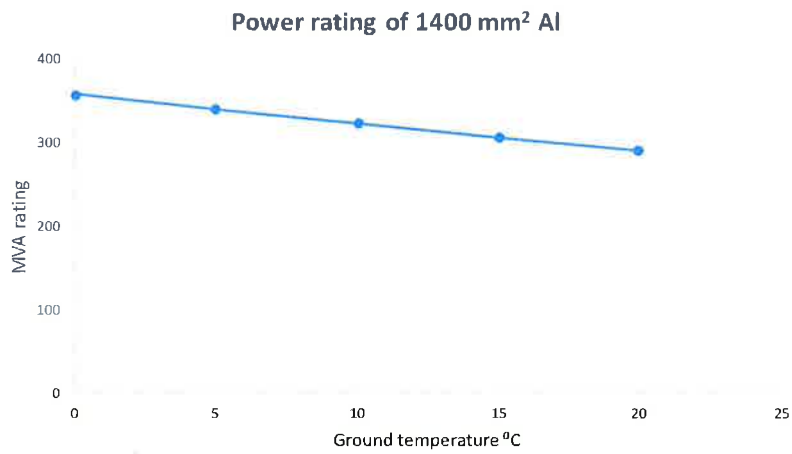


Figure 2-10. Apparent power rating for a cable system with 1400 mm² Al cable conductors.

The ambient temperature also affects the underground cable rating as can be seen on the above figure. With the power rating at 323 MVA at 10ºC ground temperature, which is near the summer mean value in Iceland, the rating will be as low as 291 MVA at 20ºC, which is near European mean summer values. At Sprengisandur, the ground temperature during summer can be assumed to be as low as 5ºC, allowing a power rating of 340 MVA.

2.3.3 Installation Depth and Arrangement

Laying depth and arrangement with respect to cable route requirements need to be defined. A laying depth of 1.0 – 1.2 m is generally used as a reference value in order to ensure acceptable cable protection. Minimum laying depth is often stated in regulations, but in addition some other cable route requirements can affect the minimum laying depth requirements. Increased laying depth generally decreases the MVA rating of the cable, e.g. increasing the laying depth from 1.0 m to 1.5 m will decrease the MVA rating by approximately 5%. Installation matters are discussed in more detail in chapter 3.

As discussed in chapter 2.2, there are two main arrangements for directly buried cable i.e. trefoil and flat arrangement. The main advantages of trefoil arrangement over flat arrangement are a lower inductance and lower space requirements. On the other hand, flat arrangement will result in a higher current rating than trefoil arrangement. Typical values are that flat formation with typical spacing of (70+D) mm will have a 6.5% higher current rating and considerably higher inductance than trefoil formation with no spacing between outer jackets. Therefore, many factors must be considered for each individual cable system when determining the laying arrangement.

As shown on figure 2-6, a basic flat formation with (120+D) mm at 1100 mm depth has been selected for the purpose of this study. The trench depth is 1200 mm and the first 100 mm are filled with thermal backfill material prior to laying the cables. The trench width at the bottom is 1000 mm for one cable circuit. Spacing of 120 mm instead of 70 mm between outer jackets does increase the current carrying capacity of a 220 kV - 2000 mm² Al cable around 1-3 % but increases the impedance (i.e. the reactance) around 8-10%. This means that where the impedance is of significant value for the cable system (e.g. due to voltage drop or different circuit loading), the distance between outer jackets should be considered carefully.

2.3.4 Cable Screen Bonding

As described in chapter 2.1, the purpose of the cable screen is to eliminate the electric field outside the cable, to provide a return path for the capacitive charging current of the cable, and to equalize dielectric stress around the insulation. There are three options of connecting the cable screen; both ends bonding, single point bonding, and cross bonding. Taking the both ends bonding method as a first choice for reasons of safety and simplicity, the criteria for selecting single point bonding would be to reduce the value of the screen current and thus the cable losses, which increases with cable length. Single point bonding does, however, mean that voltage will be induced on the open end, which then must be terminated with a sheath voltage limiter and insulation to eliminate danger due to touch voltage. Cross bonding arrangement implies a combination of these methods. With cross bonding, the cable screen is earthed at both ends but the screens are sectionalized and cross-connected between phases in order to eliminate the screen circulating currents. With this scheme, a voltage will be induced between screen and earth within the cable route, but no significant current will flow. The maximum induced voltage will appear at the link boxes for cross-bonding, which are furnished with sheath voltage limiters. This method permits a cable current-carrying capacity as high as with single-point bonding but considerably longer route lengths. A related matter for longer cable routes is the transposing of phases for the purpose of equalising the impedance between phases, which may be required in some applications but does complicate the laying process considerably.

Therefore, based on a given cable length and power rating requirements, the optimum method needs to be selected where screen current (losses), induced screen voltages, and increased cost and maintenance due to cross bonding need to be evaluated together.

Figure 2-11 shows the screen bonding scheme selected for the Sprengisandur case, which will be described further in chapter 5.

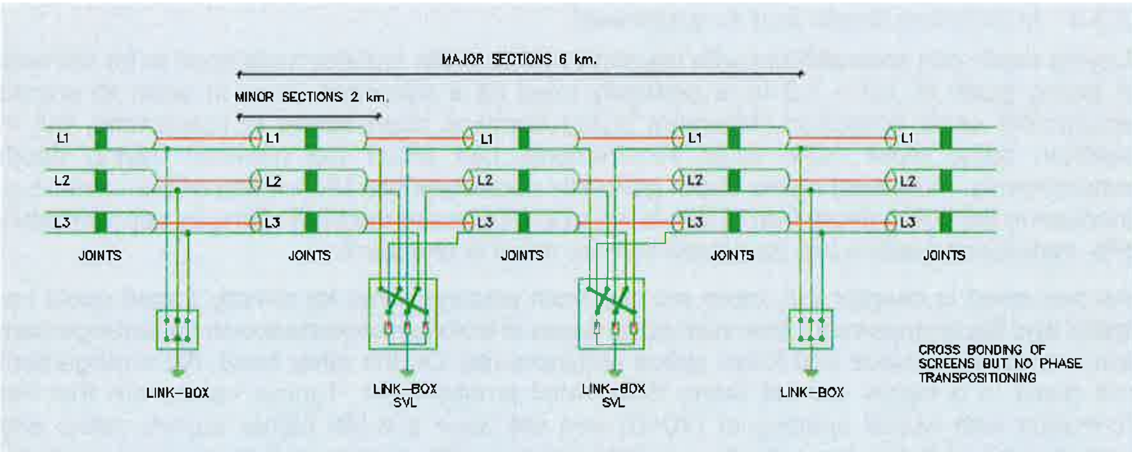


Figure 2-11. Typical cross bonding scheme.

2.4 Selection of Ancillary Materials and Equipment

2.4.1 Reactors and High Voltage Switchgear

When installing long cables, reactive power compensation (i.e. shunt reactors) may be needed due to the high shunt capacitance of high voltage underground cables, resulting in high voltage levels. This effect is prominent for lightly loaded cables.

The first choice of placing a shunt compensation reactor is at the substations close to the cable end connections. If the cable section is located between overhead line sections, the next alternative for connecting a shunt reactor is directly at the cable end. In case of high degree of compensation it may be necessary to split the reactor in two or more parts and install at both cable ends. The final selection of reactor size or compensation degree, number of reactors, use of tap changers, and location of the reactors depends on the network and operation conditions in each case. For a directly connected reactor it is essential that it is energised together with the cable section.

Figure 2-12 illustrates the impact of different placement of the reactors on the voltage along the length of the cable.

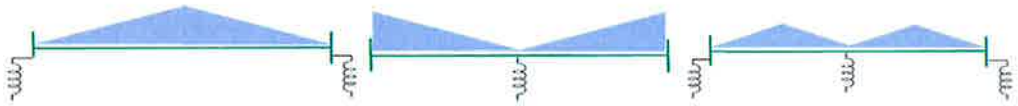


Figure 2-12. Impact of different placement of reactors on the voltage along the length of the cable.

When a long underground cable section is compensated by a fixed reactor, the so called zero-miss phenomenon may occur. This applies to the case when the breaker current does not cross zero for some periods due to a decaying DC-component of the current. If the cable compensation is more than 50%, a DC-component may incur in the current which the breaker has to disrupt. The breaker is only able to disrupt the current when it crosses zero and if the DC-component is large enough, the breaker is unable to operate for some periods and this may lead to a breaker failure.

The zero-miss phenomenon is only a problem if the cable being energised has one or two faulted phase(s). There are ways of avoiding the possibility of zero-miss, for instance controlled energisation of the cable section (i.e. point on wave). If the section is energised at the voltage maximum in each phase, the zero-miss may be avoided.

In the case of zero-miss, the current in the faulted phase(s) will be large enough to be interrupted, whereas it will not be possible to interrupt the healthy phase(s), possibly leading to very high voltages due to ferro-resonance and potential danger for generators and other equipment. It is therefore both for security reasons and for the protection of equipment that we account for zero-miss when designing a complex cable system.

Further, the high voltage switchgear for the cable needs to be selected based on evaluation of the capacitive switching current capability against the no load current of the cable.

2.4.2 Protection Equipment

For most 220 kV and 132 kV lines and cables in Landsnet's transmission system, a fault clearing time of 100 ms is required. To achieve this, the protection systems are designed as redundant systems where a failure in one protection relay or other system components will not affect the system's ability to detect and clear HV system faults.

The protection functions applied are:

- Distance protection
- Earth fault protection
- Differential protection
- Breaker failure protection

These systems are equipped with various ancillary functions, such as disturbance- and event recorders, analysing tools for fault values and distance-to-fault estimation, trip circuit supervision and CT/VT supervision. Further, the protection systems are provided with control functions, such as auto-reclosing, point-on-wave control, synchro-check, and trip-transfer.

For cable systems, fibre optic cables are also laid along the cables, to be used for differential protection and other electrical based protection functions, as well as cable phase temperature monitoring. It is envisaged that FO-based conductor temperature monitoring will be applied for most 220 kV and 132 kV cables in Landsnet's transmission system.

For cable systems that are equipped with compensation shunt reactors, special care has to be taken for the potential danger of zero-miss when energizing the cable in the event of failure on one or two phases. The actual value of the line compensation degree must be monitored and regulated to be lower than a defined level during energisation, theoretically not higher than 50% but higher levels may be allowed with certain precautions.

When a line includes overhead lines with a cable section, auto-reclosing cannot be applied without restrictions. To achieve this, the current in the cable section must be monitored separately and used to block auto-reclosing on a given phase if a fault is present. For cable sections that are located in remote areas, i.e. far from the protection equipment and circuit breakers, it is envisaged to install one high output voltage transformer to provide the electrical power required for the protection equipment.

2.5 System Analysis

Each underground cable project requires a separate system study. In this sub-section a special attention is given to the main issues that need to be considered when doing system analyses for underground cable projects. For reference, figure 2-13 shows the primary results of the system study for the Sprengisandur case, which is described in chapter 5.2.4 (Compensation requirements and critical length).

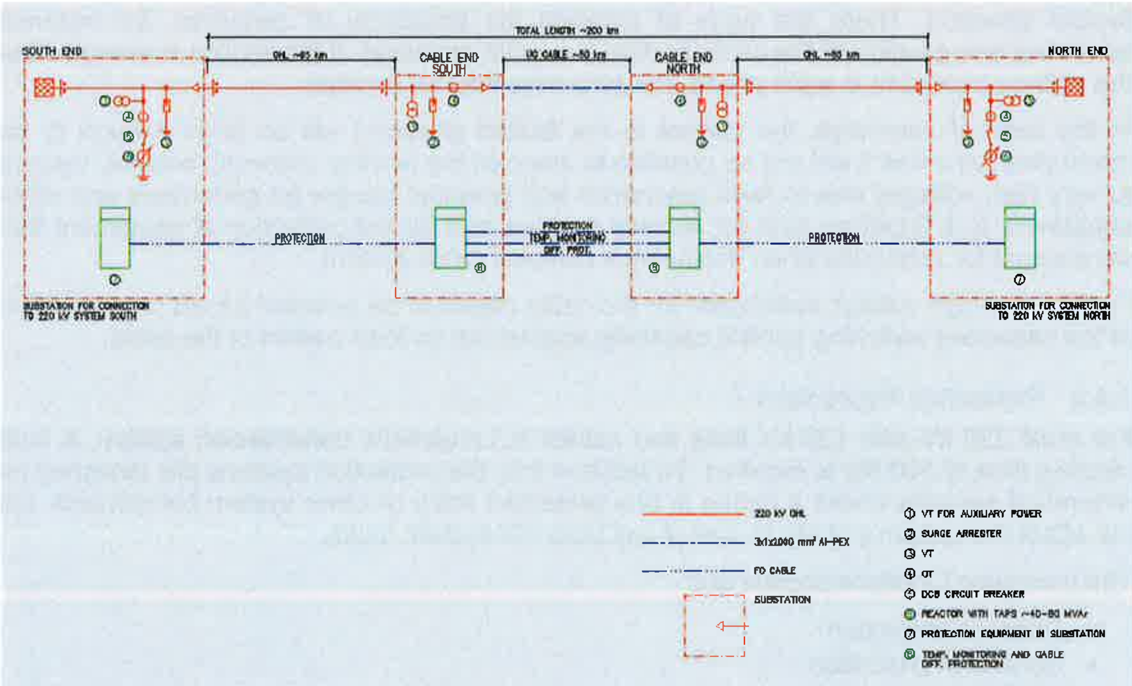


Figure 2-13. System configuration for the Sprengisandur case.

2.5.1 Compensation Requirements and Voltage Profiles

An underground cable acts as a capacitor when voltage is applied. Due to the physical structure of the cable, it produces reactive power when energised. The amount of reactive power increases with the length of the cable. As the amount of reactive power is proportional to the square of the voltage, it is obvious that as the operating voltage increases, so does the reactive power, and it can become quite high. The reactance of the cable system will consume reactive power when current flows through the system and so partially compensate for the reactive power produced. This means that the resulting reactive power is strongly dependent on both voltage conditions and load conditions.

The reactive power generated will eventually lead to problems with the system's operation. It is a part of the total power transmission capacity of the cable, thus reducing the capabilities of the cable to transmit active power. However, the most severe drawback is the influence of the generated reactive power on the system voltage. Reactive power and voltage are closely related, and the reactive power generated by the cable may lead to an unacceptable rise of the system voltage. This is closely related to the short-circuit capacity, i.e. the "strength" of the system. The higher the short-circuit capacity is, the less influence of the reactive power on the system voltage. In the Icelandic system, with its relatively low short-circuit capacity, the influence of increased reactive power on the system voltage is quite prominent.

To solve these problems, some means of compensation must be applied. The most straightforward way is to install shunt-connected reactors. The size and location of these reactors have to be chosen carefully. They must be capable of providing the necessary compensation for the whole operating range of the cable, i.e. from low-load to high-load situations. Special attention must be given to the case of energising the cable. With one end connected and the other one open, the voltage at the open end may become quite high (the Ferranti effect). This is described by the following equation:

Equation 2-2

$$V_r = \frac{V_s}{1 - \frac{\omega^2 LC}{2}}$$

where V_r is the open end voltage

V_s is the closed end voltage

L is the total reactance between closed and open ends

C is the total capacitance between closed and open ends

ω is the system frequency in rad/sec

To cope with the Ferranti effect, an additional switchable reactor may have to be applied on the receiving end, i.e. one (or more) step(s) may be needed for this open end situation. Also, restrictions may have to be put on energizing the cable from one end rather than the other. This is often the case where there is a significant difference of short-circuit capacity between the two ends. For instance, energizing the cable from the end with lower short-circuit capacity may lead to a very high voltage at that end (V_s in the formula above) resulting in an even higher voltage at the open end.

The Ferranti effect may also be experienced during load rejection and line tripping.

The most effective location for the compensating reactors is at each end of the cable. Depending on the length of the cable and operating voltage it may be necessary to install one or more additional compensating units along the cable route.

One measure on the critical length of the cable, i.e. the maximum length of the cable, is the voltage criterion which is described with the following equation:

Equation 2-3

$$L_{crit,v} = \sqrt{\frac{2}{X' * B'}\left\{1 - \frac{1}{\Delta U}\right\}}$$

with X' as the reactance of the cable in Ω/km; B' as the susceptance of the cable in S/km and ΔU the allowed per unit rise in voltage along the whole line (i.e. $U_{max}/U_{max,operation}$), including cable section.

This criterion defines the voltage rise due to the Ferranti effect, i.e. the phenomenon of the voltage at the receiving end of a transmission line being higher than the voltage on the sending end. This effect is more prominent for higher system voltages and longer lines, and much more prominent for underground cables than overhead lines due to the capacitance. Therefore, the length of the cable section represents a dominant factor.

With typical values for X' and B' for 220 kV overhead lines and 2000 mm^2 Al cable as an example, as well as ΔU = 1.05 pu, the calculated value for $L_{crit,v}$ of the cable section is approximately 80 km. The reason for selecting a 2000 mm^2 Al cable in this example is that this size of cable is commonly selected for transmission capacities up to 400 MVA and moreover that this cable cross section has been selected for the Sprengisandur case.

The parameter ΔU is the ratio between the voltages at each end of the section, i.e.

$$\Delta U = \frac{U_{max}}{U_{s,operation}}$$

where U_{max} is 1.1 pu (i.e. the maximum allowed voltage at the open end) and $U_{s,operation}$ is the operating voltage at the sending end.

When energising the cable from one end, the voltage at the other end (i.e. the open end) must be kept within the upper limit of 1.1 pu, so if the voltage at the other end, $U_{s,operation}$, can be kept as low as possible the critical length can be extended.

In general, the critical length as a function of voltage at the sending end can be found from equation 2-3 above, and shown in figure 2-14.

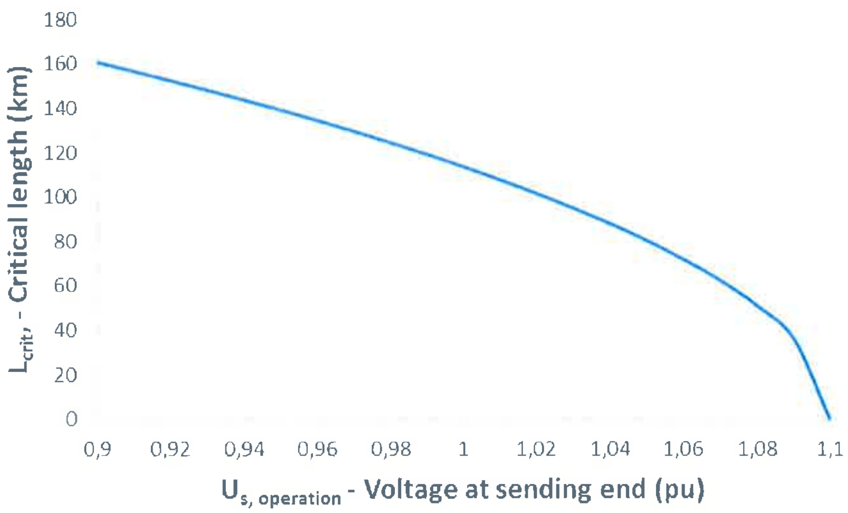


Figure 2-14. Critical length as a function of the voltage at the sending end.

The voltage at the sending end depends on a number of factors. The voltage set-points of nearby generators can be temporarily lowered to a certain point. The short-circuit capacity, which is indicative of the system strength, at the connecting point is also a very important factor with respect to the voltage at the sending end, as already pointed out. The higher the short-circuit capacity, the stiffer the voltage is, thus the easier it is to maintain the voltage at a relatively low level, which increases the critical length. Due to the physical characteristics of the cable, each km of cable produces reactive power (Q_C) that increases the voltage by an amount ΔV. The relationship between the short-circuit capacity, reactive power generated by the cable, and the voltage increase may be approximated by the expression

$$\Delta V \approx \frac{Q_C}{S_S}$$

where S_s is the short-circuit capacity at the point in question. As the expression implies, the higher the short-circuit capacity is, the lower the voltage rise is. An assessment of the impact of the short-circuit capacity on the voltage at the sending end of a typical, open-ended, 220 kV 400 MVA cable is shown in figure 2-15 below for cable sections stretching between 0 and 50 km.

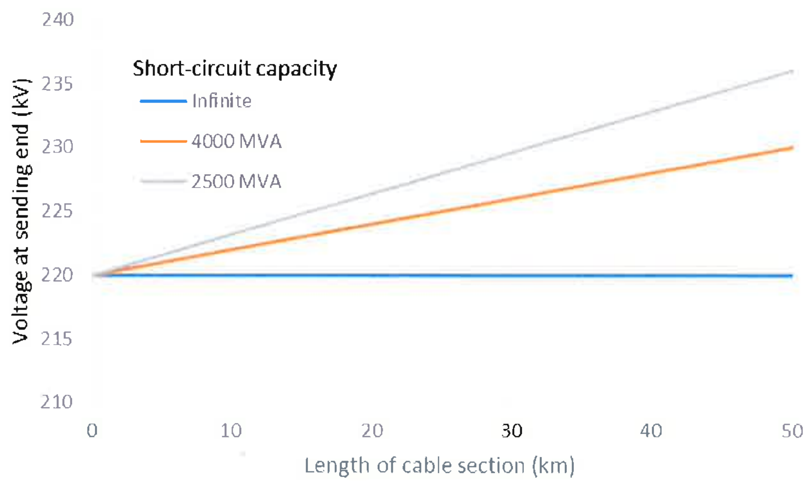


Figure 2-15. Assessment of the sending end voltage for an open-ended 220 kV UGC for different values of short-circuit capacities.

From the equation describing the Ferranti-effect, it is obvious that this impact on the sending end voltage also has great impact on the voltage at the open end.

The sending end voltage can be reduced by installing compensating reactors. Care must be taken when installing reactors compensating more than 50% of the reactive power production of the cable. If there is a fault on one or two phases of the cable when it is being energised, one will run into the risk of the zero-miss phenomenon, discussed in chapter 2.4.1 above. However, there are means of solving this problem, as described in (12).

All the voltage considerations above are concerned with energising the cable. During normal operation, more (or less) compensation may be needed. This depends on the power flow along the section; short-circuit capacities on each end; and the status of the system in general. Thus, each case has to be studied thoroughly.

2.5.2 Ampacity Criterion

This criterion, perhaps more appropriately called "active power criterion", defines the critical length of the cable with respect to the maximum allowed reactive power over a defined transmission line. Here, the critical length of the cable section is calculated with respect to the ratio of active power to the nominal apparent power of the transmission link:

$$pu_{active} = \frac{P}{S_{nom}}$$

For instance if the respective values are P=300 MW and S_{nom}=400 MVA then pu_{active} = 0.75.

The critical length can be calculated as follows:

Equation 2-4

$$L_{crit,a} = \frac{1}{2 \cdot \beta} tan^{-1} \left\{ \frac{2 \cdot P_c \cdot S_{nom}}{P_c^2 - S_{nom}^2} \sqrt{1 - pu_{active}^2} \right\}$$

The tan^{-1} function must be applied in radians.

With Z_L as the surge impedance ($Z_L = \sqrt{\frac{L'}{C'}}$), P_c is also known as surge impedance loading (SIL):

$$P_c = SIL = \frac{U_{L-L}^2}{Z_L}$$

β represents the propagation constant of the line:

$$\beta = \sqrt{L' \cdot C'}$$

If L' and C' are given in H/km and µF/km respectively, the propagation constant receives the unit /km Thus, the resulting length will be in km.

With typical values for L' and C' for 220 kV overhead lines and 2000 mm² Al cables, the calculated value for $L_{crit,a}$ of the cable section is approximately 100 km.

In general, the ampacity criterion is wider than the voltage criterion, i.e. gives higher values for the critical length, because it does not take into account the impact of the generated reactive power on the system voltage. It is preferably applied in economic considerations, e.g. when assessing if it would be more economical to choose a larger (and more expensive) cable to increase the overall transmission capacity (and thus increasing the amount of active power transmitted).

2.5.3 Energising and De-energising

As discussed in the previous section, restrictions may have to be imposed on energising an underground cable with respect to voltage rise. Attention must also be given to possible inrush currents. Special focus must be on cases where an underground cable and transformer are energised together.

The length of the cable section has direct impact on the amplitude and frequency of the inrush current. Also, the short circuit capacity at the busbar is of great importance. The lower the short circuit capacity, the greater the amplitude and frequency of the inrush current (13).

Due to the high capacitance of underground cables, systems incorporating long underground cables will experience lower resonant frequencies than pure overhead line systems. The short circuit capacity at the point of connection is another important factor with respect to resonant frequency, since the per-unit resonant frequency, h, can be estimated by the following equation:

Equation 2-5

$$h = \sqrt{\frac{MVA_s}{MVA_c}}$$

where MVA_s is the short circuit capacity at the cable's connection point (including any compensating reactors) and MVA_c the reactive power of the cable at nominal voltage (13).

Thus, the lower the short circuit capacity is, the lower the resonant frequency is for a given cable length.

2.5.4 Losses

The process of determining the type of cable conductor for a given application is an iterative process. Basically, conductor material is either aluminium or copper, but a number of conductor configurations are available for fulfilling the required current carrying capacity (e.g. stranded, solid, Milliken configurations). These conductor types will be different in various ways, including initial cost and operation losses. Their performance will also depend on various external factors, such as backfill materials, ground temperature, screen configuration etc.

For most small and mid-size power cable projects in Iceland, the way of determining this has been to calculate the required current carrying capacity and voltage drop and select the smallest stranded aluminium conductor that will, according to current rating calculations, be able to carry this current within the defined temperature and voltage drop limits. This prescribed cable type will then be tendered and the bidder that offers this cable type for the lowest purchase price will be selected.

The power transformer industry (including reactors) has for decades used a different approach for transformer design. Here, it is well known that two different transformers can be identical in terms of nominal voltage, turns ratio, nominal power etc., while at the same time, they can be very different in terms of losses and initial cost. This means that it is possible to design a lower cost transformer with higher losses by means of material quantities and design aspects. This lower initial cost will however suffer during the lifetime of the transformer due to the cost of higher losses. To eliminate this factor, it is common to evaluate not only the initial cost for selection of the successful bidder. The bidder must also state the expected power losses in his transformer, both load losses and no-load losses. These losses will then be multiplied with prescribed cost in EUR/kW for either and the resulting value will be added to the initial purchase cost for the purpose of bid evaluation. The bidder that offers the lowest sum of initial costs and loss costs will be the successful bidder. This does, however, require that the actual losses are measured during factory acceptance tests and if the actual losses exceed the guaranteed losses the respective EUR/kW amount will be deducted from the purchase price.

As stated above, this approach is common in the transformer industry and all transformer manufacturers have certified test labs and test generators to generate the power for the full load and no-load tests. This method has in recent years gained attention in the electric power cable industry and for many projects the owners and the contractors have agreed to determine the cable losses via calculations based on resistance measurements for full load losses and dielectric losses measurements for the no-load losses. This approach allows the bidder to optimise the cable design so that the resulting combined bid evaluation price will be as low as possible. This will benefit the owner as well, provided that he has calculated the loss costs correctly.

This report will not discuss the calculation of loss costs, as it is well known from the procurement / bidding process for transformers. This evaluation depends on power- and energy costs in each country as well as on the estimated voltage- and load profile (load factor / load duration curve) of individual systems. As the loss cost implies an estimate of the net present value of future costs, other factors such as interest rates and economical lifetime also factor in these calculations.

As a result, it can be stated that for large power cable projects, it is definitely of advantage for the cable owner to state a price for losses and construct the bidding procedure so that the loss costs will be added to the purchase costs. This procedure will allow the bidder to optimise the cable design (especially with focus on conductor size and conductor complexity) to result in the lowest total cost for the whole economical lifetime of the cable system. The bid documents and bidding procedures are then designed so that the cable has to fulfil certain current (or power) rating requirements, but a certain conductor cross-section, -material or -design is not prescribed. This will be the result of the bidder's optimisation process. If the cable owner has certain preferences of cross-sections, this must be stated in the bid documents.

2.5.5 Section Lengths and Number of Joints

Keeping the number of joints as low as possible is of importance, since joints and terminations often cause failures in underground cable systems (14).

The weight of cable drums may be a limiting factor, thus influencing the section lengths and number of joints.

2.5.6 Reliability of the Cable Systems

As mentioned in chapter 2.5.5, failures in underground cable systems are often related to the section joints and cable terminations. By introducing reactive compensating equipment (i.e. shunt connected reactors), one is increasing the number of terminations at the same time. Additional components may also be introduced (e.g. reactors, circuit breakers), each having their own expected failure rate. Thus the overall failure rate of the cable system (i.e. including the reactive compensating components and associated equipment) will rise.

In a recent survey, conducted by ENTSO-E and presented at the CIGRÉ session in Paris, August 2014 (15), the majority of faults in underground cable systems on voltage levels above 132 kV resulted in outage times in the range of 3 – 4 weeks. The same survey revealed that the average failure rate is assessed to be 0.28 failures/100 km/year. Thus the average outage duration is between 150 and 200 hrs/year.

The results from this survey differ from a survey conducted by CIGRÉ and published in 2009 (14), shown in table 2-1 below.

Table 2-1. Failure rates of XLPE type land cables between 2000 and 2005 (14).

XLPE - cables		60 – 219 kV	220 - 500 kV
A. Internal origin			
Cable	Failure rate [fail./yr 100 cct. km]	0.027	0.067
Joint	Failure rate [fail./yr 100 comp.]	0.005	0.026
Termination	Failure rate [fail./yr 100 comp.]	0.006	0.032
B. External origin			
Cable	Failure rate [fail./yr 100 cct. km]	0.057	0.067
Joint	Failure rate [fail./yr 100 comp.]	0.002	0.022
Termination	Failure rate [fail./yr 100 comp.]	0.005	0.028
C. All failures			
Cable	Failure rate [fail./yr 100 cct. km]	0.085	0.133
Joint	Failure rate [fail./yr 100 comp.]	0.007	0.048
Termination	Failure rate [fail./yr 100 comp.]	0.011	0.050

As with all statistics, care must be taken when interpreting the results. Average values are never anything else than average values. E.g. neither of the surveys mentioned above differentiates between cables in rural and urban areas. The cable failure rates in the table above are related to failure per year for every 100 circuit km. For shorter cable systems, the failures in joints and terminations will be of greater importance.

2.5.7 Cable Maintenance and Repair Requirements

There is normally a limited need for cable maintenance, although the route must be checked for new obstacles such as large trees, roads and buildings. The following should be considered independently, and based on the requirements of each cable system:

- Depending on the cable system design, sheath voltage limiters (SVL) might need to be checked regularly. This is normally advised by the cable manufacturer and would require SVLs to be removed and measured to check if they are still operating properly.
- Cable terminations, depending on design, need to be checked regularly to ensure no oil/gas leakage and/or other upcoming fault causes.
- It is wise to check the grounding system regularly. With time, individual grounding wires might be damaged and the grounding resistance could change and increase considerably. This should be prevented if possible.

- The outer sheath of the cable should be checked regularly. Performing a 5 kV DC voltage test on the cable route (without removing SVLs) is sufficient.
- If repair joints are purchased together with the cable, for storage as repair spares, these need to be maintained according to advice from the cable manufacturer. This will normally be regular exchange of tapes etc.

Repair requirements can be due to a fault on cable joints, link boxes, link cables, terminations, or on the cable itself. Faults on underground cables can furthermore be divided into the following:

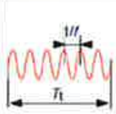
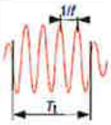
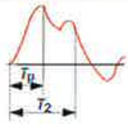
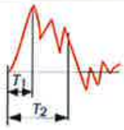
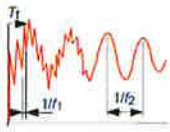
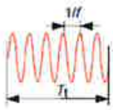
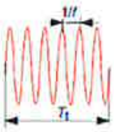
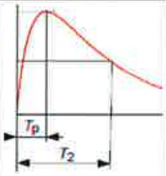
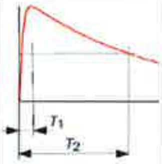
- 3rd party damage due to work in close vicinity of the cable. In most cases this type of fault causes only minor damage to the outer sheath of the cable, which can be repaired. In severe cases, however, this will require a removal of minor parts of the cable with jointing work.
- Fault due to poor workmanship. This type of fault will appear in joints, link boxes and/or terminations. It is caused by poor workmanship during on-site jointing and can be due to dirt or water in the joints, termination and/or link boxes, and can often be experienced during commissioning. However, if the fault is caused by water coming into the joint (due to poor taping etc.), the fault may not be identified until some weeks or months after commissioning. The joint will have to be opened and most often exchanged. In cases where water has gotten into the cable, it should be examined for longitudinal water flow. In case of water in the link box, it must be ensured that water cannot penetrate to the joint, through the link cables.
- Installation faults will appear due to incorrect installation of the cable system. This can for example be due to incorrect cross bonding in the link boxes.
- Production faults will normally be in the inner insulation of the cable or core conductor. This type of fault can be due to poor work during the changing of rollers during the production of long length core conductor, and will be identified by high resistance in resistance measurements as part of the routine test. Faults in the insulation will be caused by dirty particles entering the material during extruding of the cable. This fault should be identified during impulse testing, as a part of the routine test. In most cases, production faults should be identified before the cables are installed on-site.
- Faults due to ageing can appear due to changes in the heat of the surroundings of the cable, or due to unknown hotspots. If the cable experiences higher temperatures than foreseen in the design requirements, and over a long period of time, the cable can fail. This type of fault is not common and can be prevented by use of DTS systems.

In order to prevent long outages during a cable fault, it is essential to have well established repair procedures. It is necessary to know how to perform prelocation and pinpointing of sheath faults, as well as to know who to contact and to have easy access to spare components. This could include cables, joints, link boxes, link cables, fibre optic cables, terminations and/or sheath voltage limiters. It is also important to make sure that all spares are well stored, maintained and ready for use if required.

2.5.8 Insulation Coordination

In a cable system, as for an overhead line system, there is a risk of over-voltage during lightning, switching or system resonances. It is therefore important to perform a full insulation coordination study as a part of the system studies.

According to IEC 60071, over-voltages are classified based on the frequency range. Temporary overvoltage (TOV) can last for up to ten minutes. Switching over-voltage (SFO) can last up to multiple ms. Lightning overvoltage (FFO) can last up to multiple μs and very fast overvoltage (VFO) have a duration of only up to 1 μs. VFO normally only exists for GIS equipment and are studied by the manufacturer of the GIS. The IEC 60071 definition of over-voltages is shown in figure 2-16.

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3\ 600$ s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t [a]	 48 Hz ≤ f ≤ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs	a
Standard withstand voltage test	a	Short-duration power frequency test	Switching impulse test	Lightning impulse test	a

[a] To be specified by the relevant apparatus committees.

Figure 2-16 Over-voltages to be studied in an insulation coordination, as defined by IEC 60071-1.

Insulation coordination studies must follow a defined procedure, in order to make sure all cases of switching are included. It is important to define the study cases based on the actual system and realistic switching possibilities. For long cable-lines or cables with reactors, it is important to also perform a study of system harmonics and make sure there will be no over-voltages due to these harmonics. The relevant studies have already been defined for cable systems, and should be adjusted to the system in question (16), (17) and (18).

2.6 Cable Site Testing

This section describes briefly the testing that is proposed for 132 kV and 220 kV underground cables at site. These tests come as an addition to all factory tests (type tests and routine tests) according to the international standards IEC 60840 and IEC 62067, which will be obligatory.

The site tests, i.e. tests after installation, can be classified as follows:

1. DC test ("Megger") on main insulation integrity of individual cable sections.
2. DC test on outer sheath integrity, in accordance with IEC 60229.
3. Time Domain Reflection measurement, for "virgin-fingerprinting" of the cable, joints and terminations.
4. AC test on main insulation integrity (tests requiring grid voltage or tests requiring an individual power source and test transformer).
5. Impedance measurements.

A brief description of each category is as follows:

1. DC test: This simple test is conducted on new cable installations with a Megger instrument, on each cable section after laying and prior to the jointing of the cable. The DC voltage is limited to 10 kV and is intended to detect major inner insulation

faults that may have occurred during transport and laying. The voltage is not sufficient for detecting minor faults that may evolve to major faults when energised with nominal AC voltage.

2. DC test on outer sheath integrity, in accordance with IEC 60229: This test is conducted for the first time in the factory and may be repeated after arrival of individual cable drums at site. Sheath tests on arrival at site will, however, not be foreseen for Landsnet's projects, as the main rule will be that the contractor will be responsible for the cable transport. The test may be made by the contractor to ensure that the outer sheath of the cable section on the respective drum is unharmed after transport. Do note, however, that the test will be obligatory after installation, i.e. after laying and covering with the thermal backfill layer. For longer cable routes with cross-bonding of screens, the test will be conducted for the sections between cable screen link boxes. The test voltage will be decided individually for each project, but will in most cases be 10 kV DC.

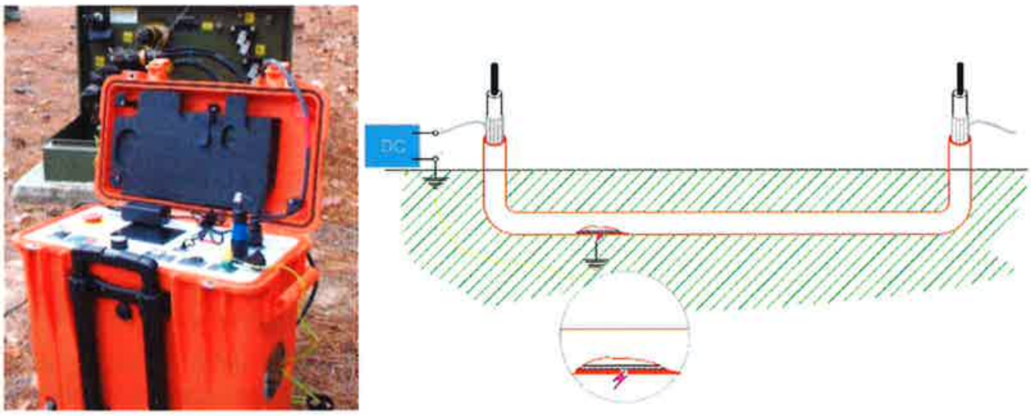


Figure 2-17. Sheath test arrangement and -equipment.

3. Time Domain Reflection test: This test is conducted with a dedicated measuring instrument, generating test pulses with short rise time and detecting the reflections. The reflections will be depending on the cable impedance along the cable route and all "discontinuities" in cable impedance can be localized and displayed graphically. This applies for all cable joints and other deviations from the "normal" and "undisturbed" cable route. The discontinuities can be absolutely harmless, but may also be potential weak spots in the cable route. Therefore, it is useful to map their locations and amplitudes prior to first energizing of the cable. If the test is repeated later, the new measurements can be compared to the initial measurements. If everything is normal, no prominent changes from the original pattern should be detected or reversely, all prominent changes can be an indication of a fault location.

4. AC test on main insulation integrity: After the cable has been laid and all joints and terminations are ready for energizing, the cable should be subject to a voltage test prior to final commissioning for commercial operation. According to IEC 60840 (for 132 kV) and IEC 62067 (for 220 kV), the AC test voltage to be applied shall be subject to agreement between the purchaser and the contractor. This voltage may either be nominal voltage for 24 hours or a higher voltage for a shorter period. In most cases, a no-load test on grid voltage for a period of 24 hours is considered to be sufficient. During this time, the nominal voltage will be sufficient to discover the vast majority of possible "hidden failures" that the DC test with 10 kV did not detect.

After the 24 hour test, the cable route may be taken into commercial operation and loaded. This test will be obligatory for all of Landsnet's projects. For some projects, it may be considered necessary to apply a higher voltage for a shorter period of time, to discover all "hidden failures" that may be present in the cable route. This test does require quite extensive test equipment with diesel generators and a test transformer, among other equipment. It may be feasible to conduct a Partial Discharge measurement and/or a tanδ measurement along with these tests, both with the purpose of further determination of the cable- and joint insulation quality. For Landsnet's projects on 132 kV and 220 kV cables, this test will not be obligatory but will be considered individually for each project. Therefore, these quite cost intensive tests are not factored in the cost estimates in chapter 4.

5. Impedance measurements: Introducing of a cable section into the transmission grid will result in major changes in system impedances. This is particularly important for the interconnected grid at 132 kV and 220 kV, less for short branch-offs to individual power plants or consumers. For the purpose of system studies and calculation of protection relay settings, it is considered an obligatory part of the commissioning work in Landsnet's projects to conduct a measurement of the positive- and zero sequence impedances. This will also help to detect asymmetries due to mistakes in cable installation.

According to Landsnet's quality assurance system, it is obligatory that the network operators' department will conduct its independent acceptance tests after the contractor has finished his tests and prior to first energizing. For HV cables, this entails that Landsnet's operators may conduct their own sheath tests and TDR tests prior to the 24 hour no-load test. This will be accounted for in cost estimates, additionally to the tests conducted by the contractor.

3 CABLE INSTALLATION

3.1 General

Physical or environmental conditions significantly affect the installation and performance of underground cables. Geographical and geological conditions may vary and climate conditions, with different precipitation and temperature, may differ along a route. The thermal resistance of the soil may also be varying, even within the proposed cross section to be excavated. Other issues, such as parallel draining ditches, surface coatings of roads and paths, or even access possibilities may affect the cable performance and the installation, Hence it is important to carry out thorough route surveys and site investigations, along with comprehensive studies of potential backfills.

Design of cable trenches, and in particular infrastructure crossings, have to be carried out in close cooperation with the cable designers or manufacturers to ensure optimal selection of cable and installation methods.

The main issues when designing a cable trench cross section are:

- Mechanical protection of the cable
- Heat dissipation
- Environmental issues
- Cost related issues

Different methods of cable installation, challenges and limitations, thermal conditions of Icelandic soil, and options to improve thermal dissipation will be discussed in the following sections.

3.2 Geographical Areas, Challenges and Limitations

3.2.1 General

When selecting a cable route the obvious approach is to find a route that offers the least disruption of the surroundings. That may be complex at times due to the different stakes at hand. Areas where vegetation or surface appearance can be restored would by this means be preferred. The same applies for areas suitable for plain trenching by backhoe excavators. Rock outcrops, which require extensive chiselling, are to be avoided if possible. Most agricultural areas provide reasonably good conditions for plain excavation and surface restoring, while the drawback would be the high organic content of the soil, as explained later. In many areas, it may be necessary to lay a construction track along the trench. Such tracks may have to be removed upon completion or they can serve as maintenance tracks for the cable if approved by the landowners and respective authorities.

3.2.2 Sands

In Iceland there are extensive “sandur” formations, especially along the south coast. Eolian sands cover large and vast highland areas and fluvial sand and gravel formations frequently cover the valleys. These areas may at first glance appear suitable for cable installation, but many of these formations may have poor thermal dissipation properties and require a selective backfill. Excavation in some sand formations, especially the eolian sand, may be difficult due to low friction angle, sand drift and groundwater control, while surface finishing as such is relatively straightforward.

Figure 3-1. Proposed cable route in South Iceland.

3.2.3 Scrublands and forests

The Icelandic flora does not include many or large forested areas, as most of the elevated vegetation is scrubs. Still there are sites where the crossing of forested areas is difficult to avoid, i.e. in the Eyjafjörður case (chapter 5.4). Restoring the surface over a cable route at such location is obviously difficult and certain restrictions may have to be implemented regarding further planting in the vicinity of the cable. The root systems of larger trees can absorb the moisture from the cable surroundings and can contribute to dryout (9) (16). Trees with a deep root system (such as aspen and pine) should not stand closer to the cable than 5 meters, and trees with a more shallow root system (like birch and willow) should not stand closer than 3 meters (19).

To avoid this it may be necessary to install the cable deeper, or below the extension of the root systems. In very sensitive surroundings, horizontal directional drilling (HDD) might be an option, but such deep installation would normally reduce the cable's ampacity.

In cooperation with local planning authorities, possible treeless channels above cable routes can be used for footpaths or tracks. However, a paved surface above the cable should be avoided as this prevents natural moisture infiltration to the soil around the cable.

Figure 3-2. Installing 132 kV Rauðavatnslína (2005).

3.2.4 Lava

Extensive lava fields cover vast areas within the volcanic zones that extend diagonally through Iceland from the Reykjanes peninsula towards the northeast.

Lava formations are divided in Aa[5] and Pahoehoe[6] lavas. The first one represents thick and viscous lava flows and is normally very rough with thick scoria and loose stone rubble on the top. The surface may also be very undulating. The second one represent a thin unit of quite fluid lava flow with an even, plate like surface. These surfaces are usually more solid than the Aa lavas, with their thick scoria rubble on the surface.

Excavation through lava normally requires chiselling or blasting. There may be locations, especially in tephra filled Aa lavas, which may be suitable for ripping by heavy excavators (>45 ton).

Lavas are normally not particularly suitable for cable installation for the following reasons:

- Excavation requires chiselling, blasting or ripping by heavy machinery.
- The flora can be extremely sensitive as moss that requires decades to retrieve.
- The rough surface of the lava cannot be regenerated.
- Permeability of the lava is very high, leading to a dry and unfavourable thermal environment.
- Lava fields have by definition a certain protection status in the Icelandic conservation law.

Because of the above mentioned, routes planned through lava or areas with shallow bedrock should be planned carefully and cost compared to longer bypasses. Another option would be to place the cable in elevated fills and thereby reduce the "hard" excavation to a minimum. Such fills could then become a future track or, where roads or other tracks exist, the cable can be placed in a side fill over a shallow excavation.

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[5] Apalhraun

[6] Helluhraun

Figure 3-3. Excavation of a cable trench in lava formation near Hamranes (2007).

3.2.5 Earthquake Zones

Iceland is located on the active continental plate boundary between America and Eurasia, resulting in high earthquake activities. The largest earthquakes, capable of affecting infrastructure, are mainly confined to the transverse fault system crossing the South-Iceland lowlands and in northeast on the Tjörnes transverse faults. Other bedrock faults associated with the rift extend throughout the entire volcanic zone from Reykjanes to the northeast. Even though such faults are only associated with "moderate" earthquakes, there may be significant displacement along such features.

Earthquakes mainly affect underground cables by permanent displacements across faults and by liquefaction. Liquefaction is confined to fine grained sediments and a few locations exist, mainly in southern lowlands, where this phenomenon could be actual. The direct displacement is more relevant, as many cables already cross active faults. It is recommended that active faults and potentially prone liquefaction areas are mapped as a part of site investigations.

As the fault systems extend diagonally across the country, it can be difficult to avoid them completely. It is also difficult to ensure a completely save transition across faults as the size, timing, and exact location of such movements is very unclear. The risk associated with seismic activity can be reduced by several countermeasures. Solutions that can be implemented include to allow the cable to move freely and to extend in case of a movement in a known fault. If the faults can be accurately located it is possible to install a loop at the crossing. The cable may also be installed in a duct, in which case a longer portion of the cable would be allowed to extend. Where the faults are not well defined, or the potential movements are divided across many small faults, a snaking pattern for the installation may be a viable solution.

3.2.6 Geothermal Areas

As for the earthquake zones, it is preferable to avoid placing underground cables near geothermal areas. In some cases this is not possible. The location of geothermal surface activity can shift within given areas, for example as a result of seismic activity. If a cable has to be placed in proximity of a geothermally active area it is possible to design the cable trench so as to lower the geothermal impact on the cable. This can, for instance, be done by inserting isolation, instead of heat conductive material, under the cable or even by inserting a cooling system along the cable. Geothermal solutions need to be developed in detail for each case.

Detailed monitoring of the thermal behaviour of the cable and surroundings at such locations should always be included.

3.2.7 Groundwater

A high groundwater level at the project site can cause difficult working conditions. Depending on the soil conditions, there may be a need for more extensive access tracks as the bearing capacity of the soil is reduced. There is also increased risk of trench collapses and a need for maintaining a stable trench wall or a slope. Uncontrolled water in the trenches affects the fill, as it may wash away and affect all cable handling. The likelihood of unwanted disturbances always increases when working in very wet conditions.

The cable trenches can also act as a drainage canal later, especially if there is a great height difference along the route. If this is not desired, plugs may be installed – conceivably of clay if available. The drainage effect may cause drying out in the highest spots along the route.

Measures to control groundwater and flow along trenches include the following:

- Selective work season, dry season or perhaps winter?
- Controlled water pumping and drainage
- Diversion dams or tight barriers in trenches
- Limited length of open trench at each time
- Ground freezing
- Directional drilling
- Ploughing
- Excavation box

While many of these measures are conventional, they still need to be carefully planned and executed for best results. High water levels definitely increase cost, with the possible exception of ploughing, which is a relatively economic installation. However, the main drawback associated with ploughing is the uncertainty of the quality of installation.

3.2.8 Urban Areas

There are many things to consider when installing cables in urban areas. Restrictions regarding planning and depth are normally imposed for the cable route, and impediments such as the crossing of roads, pipes and other existing infrastructure will have to be considered. The cables are normally laid out in a tight trefoil, not only due to available spacing, but also in order to minimize the magnetic field around the cable. Magnetic fields in the vicinity of power cables and induced voltage in parallel pipes is discussed in chapters 2.2.3 and 2.2.5 respectively.

3.3 Installation Methods

3.3.1 General

During the selection of a cable route it is important to minimize the problems that can arise during the installation process. A main installation method is usually selected to cover the largest part of the route, with variations in shorter sections and at crossings. These shorter sections of the cable route can often be critical for the cable installation, calling for a special effort in their design. Therefore, a main cross-section chosen for a cable route does not always reflect the technical challenges and the total cost of the project.

Different methods of cable installation will be discussed in the following sections.

3.3.2 Traditional Excavation

The most common method for cable installation on higher voltage levels (≥66 kV) is in an open trench, excavated using traditional backhoe excavators or similar equipment. The excavated material is placed on site for later use or transported away, then reused or replaced with other materials. A number of factors affect the cable trench cross-section such as:

- Soil conditions
- Site and environmental conditions
- Safety issues
- Arrangement of the cables (trefoil / flat formation)

Several issues need to be taken into account when optimizing the trench cross-section. There is often an interaction between these issues, where lowering the cost of one factor will negatively influence another. The steepness of the slope of the excavation sides is dependent on the soil conditions as well as the time the trench is required to stand open. For the best thermal properties it is better to reduce the depth. There are, however, various factors which limit how shallow a trench can be, such as danger of erosion, frost susceptibility, and danger of cable damage caused by machinery. Basic cross-section for 220 kV cable in flat formation, suitable for Icelandic conditions is shown in figure 3-5.

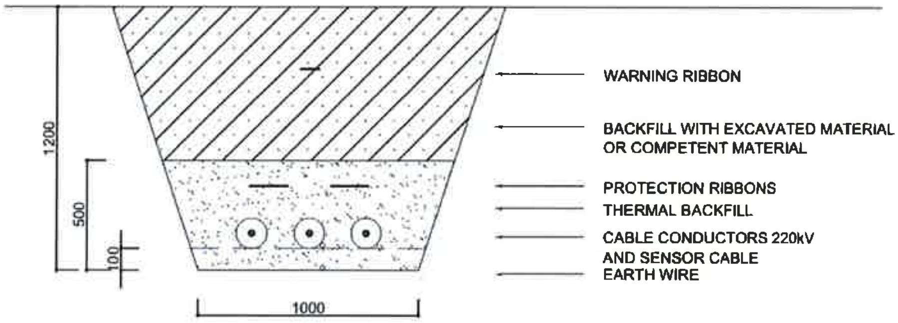

Figure 3-4. Basic cross-section, for 220 kV cable in flat formation.

Figure 3-5. Cable trench 130 kV Nesjavallalína 2 (2009).

The amount and type of thermal backfill material needed is dependent on the heat of the outer sheath of the cable (see figure 2-1), thermal resistance of the surrounding soil, and the depth of the cable. One way of minimising the cross-section is to embed the cable with a special thermally controlled concrete. The concrete behaves as controlled backfill and the heat at the interface between concrete and surrounding soil concrete becomes the critical factor, which lowers the risk of dry-out. A more detailed analysis of the available thermal backfills is presented in chapter 3.10.

If bedrock is encountered when excavating the trench, it needs to be removed in most cases. This is usually either done by blasting or by jackhammers attached to excavators. Both methods are time consuming and if the height of the bedrock is not known beforehand it will cause delays in the project. In most cases, the excavated bedrock is not suitable for backfill and needs to be exchanged with suitable backfill material.

3.3.3 Ploughing

The ploughing technic is a simple method to install underground cables and greatly reduces the area that is disturbed in the installation process. In the most suitable conditions, this method of installing cables is faster than the traditional excavation method. Ploughing can be suitable in soft, homogeneous soil, e.g. in sand, if the heat dissipation in the surrounding soil is acceptable. On the other hand, if the soil is hard or rocky, and there are many crossings on the cable route, the method can be ineffective. The ploughing method is well known in Iceland for ≤ 33 kV cables and has also been used for installing a 66 kV cable (Vestmannaeyjastrengur 3, 2013). The uncertainty of the conditions closest to the cable is always considerable, and for bigger cables this risk can be unacceptable. Specialized equipment for ploughing larger (at higher voltage level) cables exists, where thermal backfill material is placed around the cable while ploughing.

Ploughing equipment that can place backfill material around the cable has not been used in Iceland so far, but can be considered as an option within suitable areas.

Figure 3-6. Cable installation by ploughing.

3.3.4 Excavation Box

In some areas, i.e. where the water table is high, an excavation box can be used to install cables. This method involves laying out the cable beforehand along the cable route. The trench is excavated normally for a short distance at a time. The excavator then pulls the box along the excavated trench which inserts the cables and the thermal backfill at the same time. The trench is then closed directly after, using other equipment. This method is suitable when the soil is unstable.

The excavation box method has not been used in Iceland, but has for example been used for many years in Denmark for cables up to 150 kV. Until now there is no experience in using the equipment for installing 220 kV cables (16).

The initial cost of the equipment should not exclude it from being a method worth considering for installation of cables in wet areas in Iceland.

Figure 3-7. Excavation box in use in a Danish cable project (16).

3.4 Installation along existing roads

To minimize environmental impact, and where there is little space for a new cable installation, it may be possible to use existing (low traffic) roads as service roads and in some cases to install the cables into the side slopes of the road. Such an installation requires minimizing the cross-section, and of course a cooperation with the owner of the road. In general the conditions (humidity and thermal dissipation) in road material is not suitable for underground cables. Also there is a higher risk of mechanical damage. One way to minimize the cross-section, without increasing the risk of cable damages, is to use thermally conductive concrete (weak mix) around the cables instead of traditional backfill material. The concrete behaves as controlled backfill and the heat at the interface between concrete and surrounding soil becomes the critical factor, which lowers the risk of dry-out (a more detailed analysis of the available thermal backfills is presented in chapter 3.10). Figure 3-8 shows a cross-section that has been used for installation by or in the side slopes of roads in recent cable projects in France (20). As most Icelandic soil has low cohesion properties, ditches with vertical walls are normally not specified as excavation profiles. Figure 3-13 shows optimized cross-section that could be used in Icelandic conditions, if thermally conductive concrete is used around the cable.

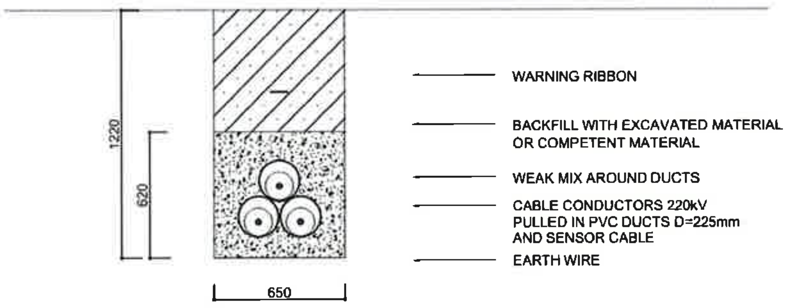

Figure 3-8. Concrete/Weak-mix section, as introduced in recent cable projects in France (20). The cost is estimated to be around 3.5 times higher than the Basic cross-section in figure 3-4.

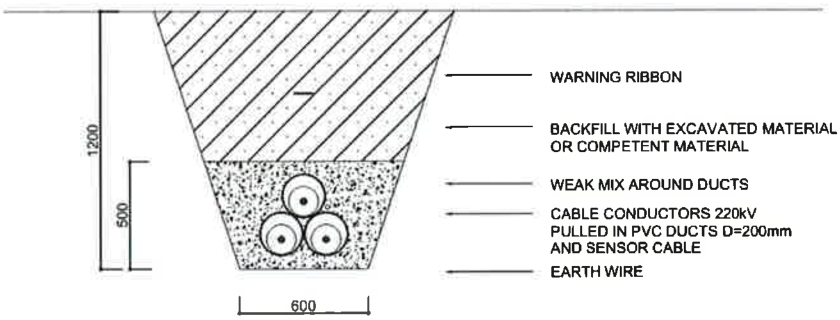

Figure 3-9. Optimized Concrete/Weak-mix section possible in Iceland. The cost of the section is estimated to be around 4 times higher than the Basic cross-section in figure 3-4.

Price comparison shows that the cost of the cross-section in figure 3-8 is around 3.5 times higher than the basic cross-section in figure 3-4, and the cross-section in figure 3-9 is around 4 times more expensive.

3.5 Crossings and Restrictions

3.5.1 General

Some objects in the landscape, such as existing structures or future planned structures cannot always be avoided. In some cases there are also municipal planning restrictions that must be followed. These things must be taken into account when choosing the cable route.

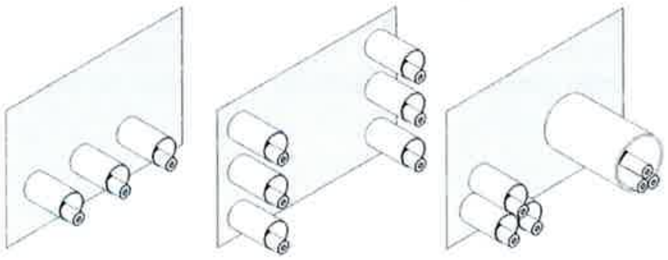

Figure 3-10. Example of cable conductors in pipes (16).

3.5.2 Public Utilities

Most cable routes need to cross various infrastructure utilities including for example: Water pipes (hot and cold), sewage pipes, electricity low/high voltage cables, and fibre optic cables.

Crossing methods include for example:

- Deeper excavation, under existing pipes
- Shallower excavation, crossing over existing pipes. This requires protective measurements such as covered pipes, concrete cover blocks, concrete around the cable, geotextiles or soil materials with certain properties
- Directional drilling (discussion in chapter 3.5.4)
- Duct ramming (discussion in chapter 3.5.5)

In most cases the route is chosen so that existing pipes and cables are not disturbed but in some cases these cables/pipes need to be adjusted to take into account the new cable. This can also involve the installation of protective measures between the cable and the existing pipes/cables such as geotextiles, concrete covers, or soil materials with certain properties.

The matter of dangerous induced voltages in pipes parallel to power cables is discussed in chapter 2.2.5.

Figure 3-11. Example of pipe crossings, Nesjavallalína 2, near the power station.

3.5.3 Rivers and Trenches

A few methods can be considered when crossing rivers, depending on size and location, such as:

- Damming the river and using normal excavation.
- Directional drilling under the river bottom, leaving pipes for cable installation.
- Ploughing pipes into the river bottom.
- Building a bridge or using existing structures for the cables.

All these options are expensive and the selection of a preferred option has to be studied specifically. Small rivers and trenches can be crossed by excavating the trench a little deeper and then installing the cable into a cover pipe. Sometimes this needs to be combined with a protective layer in the bottom of the river/creek, i.e. geotextile, gravel or concrete. Calm rivers can also be crossed using this method, although in some cases the waterway then needs to be diverted while working, which is costly and can disturb the local wildlife, and may cause restrictions regarding the allowed timing of construction.

Other methods are required for larger rivers. Directional drilling can be used to minimize the disturbance of the surface. In this case, pipes are installed through which the cable can be pulled later. If, for some reason, it is not possible to go underneath the river, a special structure can be built for the cables to cross, or existing structures such as bridges can be used. For this solution there are some technical issues that need to be solved, for example how the cables are brought from ground up to the bridge and how the safety is secured.

3.5.4 Horizontal Directional Drilling

When crossing roads, rivers, or other obstacles where environmental impact caused by the disturbance have to be minimised, horizontal directional drilling (HDD) is a possible installation method. A special drill rig is used which is capable of drilling underneath the obstacle. First, a narrow pilot hole is drilled with a steerable drill bit, capable of controlling both depth and direction. Then a reamer is drawn back through the pilot hole, both to enlarge it and to draw ducts after it into the hole. The cable is then pulled into the ducts.

Figure 3-12. Schematic drawing of directional drilling.

The cables can be placed in different configurations, either in separate pipes or within the same one. In most cases the pipes have to be filled with thermally conductive grout (e.g. Bentonite) which does not solidify. The use of pipes in cable routes can reduce power rating by approximately 5 – 10%. If the pipe is not filled with conductive grout, the power rating can reduce even further. When drilling in rock the voids outside the pipes are also filled, if better thermal properties are needed.

The success of HDD is dependent on the geological conditions of the site. If the geology consist of homogeneous material the drilling is quite predictable. If cracks, faults, voids, interbeds, or other irregularities exist in the material the drilling can be problematic. This is because the drill has a tendency to follow faults and interbeds. In addition, the risk of losing drilling fluid increases. In general, the most suitable conditions for directional drilling are weak rock with few cracks or dense sediment. As the rock gets harder the drilling is more time consuming. Conversely, if the sediment or rock is too weak and loose the stability of the hole becomes low, resulting in increased caving of the hole, and the steering of the pilot hole can be hard to manipulate.

In Iceland, HDD can be difficult due to thin soil layers and variable characteristics between parallel layers. However, where conditions on the cable route are favourable, directional drilling can be suitable.

At present there is only one contractor in Iceland with equipment for HDD. The maximum length of each separate drilling has been around 200-300 m. Contractors outside of Iceland have equipment to drill much further (over 1 km) which is an option that is desirable to explore for larger projects in Iceland. There is some experience with using HDD in Iceland. The method was used in difficult bedrock during the installation of Nesjavallalína 2, 132 kV (2009) and Vestmanneyjastrengur 3, 66 kV (2013). Even though the method is more costly than traditional excavation, it is still sometimes the best or only method available.

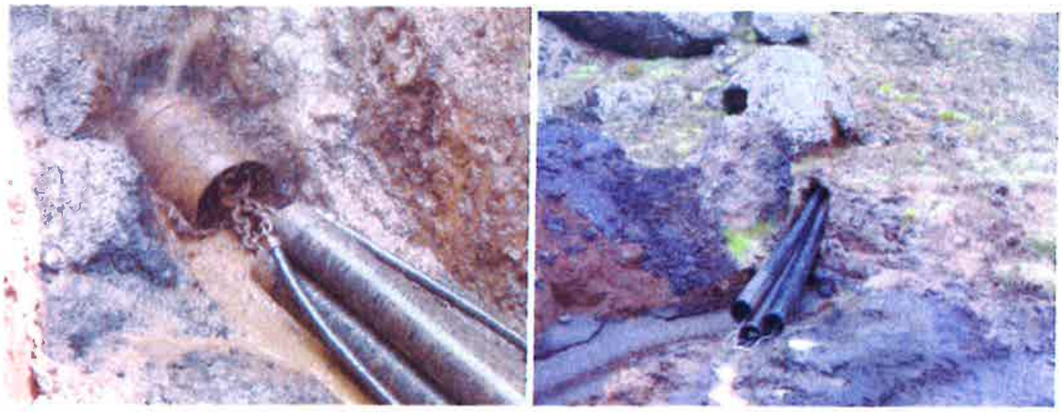

Figure 3-13. Underground drilling at Dyradalir, during the installation of Nesjavallalína 2 (2009).

3.5.5 Duct Ramming

When the cable route crosses a road, the cable can be installed into ducts that are rammed through the base of the road. Duct ramming is a widely used method for smaller road crossings and is performed by hammering plastic ducts with pneumatic percussive blows through the soil. As for directional drilling, the pipes can either be filled with thermal grout or left empty.

3.6 Service Roads

During the construction period, traffic of heavy vehicles along the cable route must be assumed. In many cases the excavated material needs to be transported to a dump location and fill material needs to be transported into the site. Cable drums, temporary structures in joint bays, and other components that need to be placed along the trench can also be very heavy.

The soil along the cable trench is not always suitable for the traffic of heavy vehicles. Therefore, the construction of a service road along some parts of the trench is necessary to minimize structural damages of the soil.

A service road needs to be 3.5-5 m wide with a thickness of 0.3-0.5 m. In many cases the service road needs to be removed or hidden in the landscape in the final phase of surface finishing after the installation of the cable. In few cases, with good pre-planning, the service roads can be left for later use as a horse- or bike road for example.

The material for the service roads is transported from nearby mines that are chosen with the aim of minimising the transport distance.

In some cases it is desirable to put geotextile underneath the service road to preserve the existing surface until the road is removed.

Another method to minimize damages of the soil along the cable route is to lay steel plates along the trench during construction. This requires a significant investment in steel plates as well as a special work crew to insert and transfer the plates. Normal use is approximate 600 steel plates, with a size of 2x3 meter, along each 1 km of trench. Additionally there will be a need for steel plates on deposit sites and access lanes from public roads. As an example, Energinet.dk has recently ordered 8000 steel plates for an 8 km long cable route.

[redacted]

For project sites that are particularly vulnerable and require extensive access roads that cannot be utilized for anything else after the project is completed, the use of steel plates can be considered an option. For most projects, the high initial cost and the transportation cost means that the method is not competitive in Iceland.

Figure 3-14. Example of steel plates as a service road, from Europe (16).

Other materials could possibly serve the same purpose as steel plates, if they are rigid enough, but this has not been included in this research.

Reducing the requirement for service roads or the need for removing them is usually beneficial for the project's financial outcome.

3.7 Installation and Jointing

3.7.1 Joint Bays

When the cable route is planned, joint bays must be located, having in mind the maximum length of cable phases on each drum and access to the bay from main roads.

At each joint bay a special working area must be prepared by widening the trench. This working area has to be wide enough for the installation of a custom-built structure (covering house) and big enough for the jointing team to perform its work efficiently. The purpose of the jointing house is to prevent wind and rain disturbing the sensitive connection work. Furthermore the floor of this structure has to be kept clear and dry. Water pumping is needed in wet areas.

 

Figure 3-15. Preparation of joint bay, Nesjavallalína 2 (2009). Container as a cover in a joint bay (Europe) (16).

The detailed design of the joint bays depends on the environment and/or is sometimes specified by the cable manufacturer. For Icelandic conditions, the covering house is either made from plywood or a container is converted for the purpose. The floor can be made from removable wooden units arranged around the conductor joints. In wet areas, the use of concrete or sand/gravel in the bottom of the jointing bay is an option along with efficient water pumping. In a few cases the cable manufacturers require a concrete floor for fastening of equipment. This is mostly needed for very large cables, such as for ≥220 kV jointing work.

Portable power generators are used to provide working light and heating. For efficient work in cold weather it is convenient to have two houses for each jointing team: One is ready and even warm when jointing work is finished in the other one. This also depends on the house itself and the equipment that must be transported between joints. Specially trained jointing crews from abroad make the joints for the cable producer and waiting time is expensive.

At every other jointing bay, an area will be needed for setting up the cable drums. For a normal 220 kV project it is estimated that the cable jointing work will take 7-8 days for each location, including preparation and finishing.

3.7.2 Cable Installation

The high voltage cables arrive on large cable drums with around 1 km of cable conductor on each drum. A single aluminium conductor can weigh around 20kg/m and a copper conductor up to 40 kg/m.

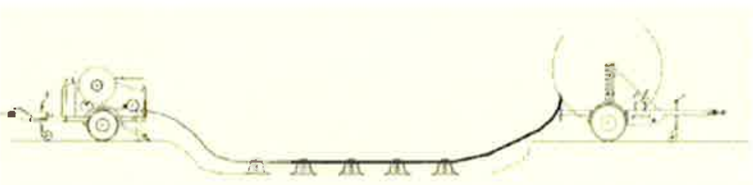

Figure 3-16. Cable drums and cable pulling. Cable drum on a special trailer (16).

A special trailer wagon must be provided so that the cable laying process is as efficient as possible. The trailer is designed so that the drums can easily be placed onto it and then the cable is pulled out into the trench. The trailer needs to have a good mechanism to control the speed of the drum when pulling the cable so that it is not damaged.

Special wheels (spacers, roll bars) are placed into the trench at certain intervals to hold the cable in place to prevent it from touching the bottom or obstacles when it is being pulled. This is necessary to prevent damage to the outer sheath of the cable. The cable is pulled slowly, phase by phase, by a winch positioned at the next joint bay. The pulling forces are limited by maximum values given by the cable manufacturer and the pull itself is controlled by people placed along the trench and at critical places, such as sharp corners. Special consideration needs to be taken when pulling out the cable in difficult weather conditions. Most cable manufacturers do not allow cable pulling at air temperature below -5°C. Thus, at low temperatures, the cable conductors need to be warmed up in tents before pulling or the work needs to be stopped completely.

Figure 3-17. Cable installation process.

3.8 Civil Structures for Compensation Reactors and Cable Ends

Compensation reactors, if required, will typically be housed in substations where other civil structures, such as high voltage equipment and other related systems, are kept. In other words, it is best if existing structures and facilities can be utilized for the compensation reactors, even though the cable section is not located immediately at the substation. It is assumed that cable ends in remote areas, where overhead lines are continued by underground cables, will be housed in completely enclosed structures. For cost estimation purposes, a preliminary design has been made as shown in figure 3-18 below.

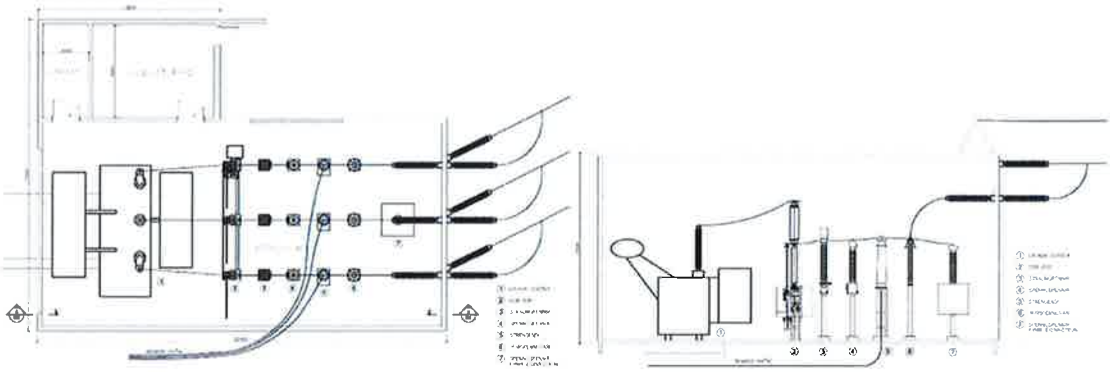

Figure 3-18. Civil structure for compensation reactors and cable ends.

3.9 Surface Disturbances and Finishing Treatment

For most cable projects, it is expected that all areas that the project disturbs will be restored. This involves fine levelling of the surface and retouching according to the surrounding surface, i.e. trying to re-establish the overall appearance of surface as it was before the project started.

In the case of a single cable set, i.e. one trench and excavated soil removed from the site, the disturbed surface is measured from the external side of the service road to the external mark caused by the excavator. If the soil is not removed, but placed by the side of the trench, an extra 2-4 m disturbance zone is created. In total a 10-14 m wide zone can be expected to be disrupted for each cable set, depending on whether the cable route is located on flat land or in a slope, the width of the service road, the stability of the trench, and how much space the excavated material will take. If two sets are installed, normally the service road would be located between the two trenches and used for installing both cable sets. Therefore the disturbance zone for a double set of cables is not double in comparison with one set, but will be around 14-22 m. Examples of a disturbance area for one and two sets are shown on the figures below (figure 3-19 to 3-21).

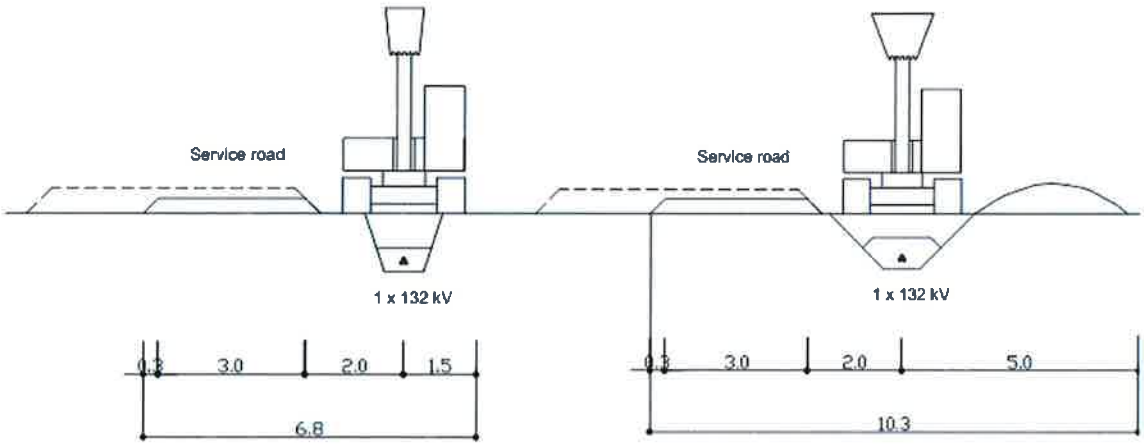

Figure 3-19. 132 kV cable, minimum cross-section with service road. On the left excavated soil is removed from site. On the right excavated material is placed beside the trench.

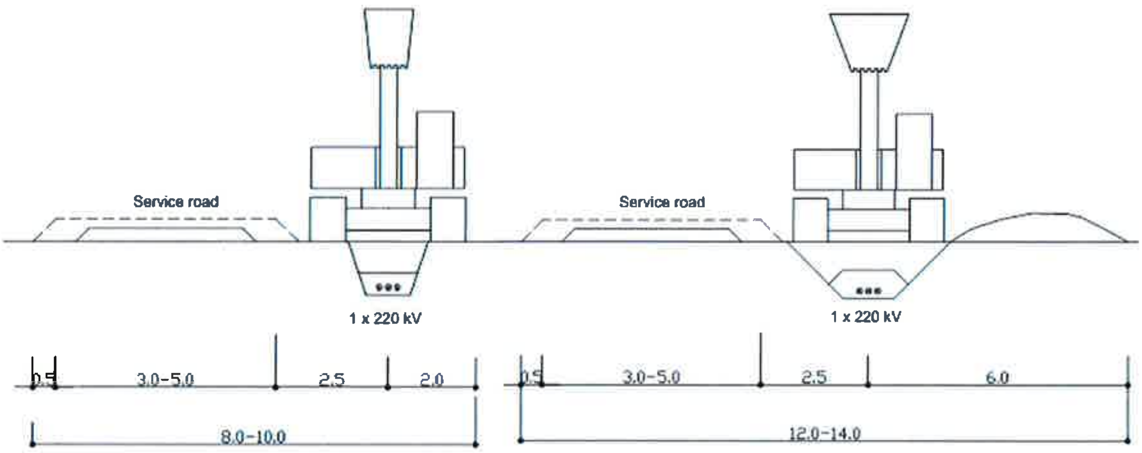

Figure 3-20. 220 kV cable, minimum cross-section with service road. On the left excavated soil is removed from site. On the right excavated material is placed beside the trench.

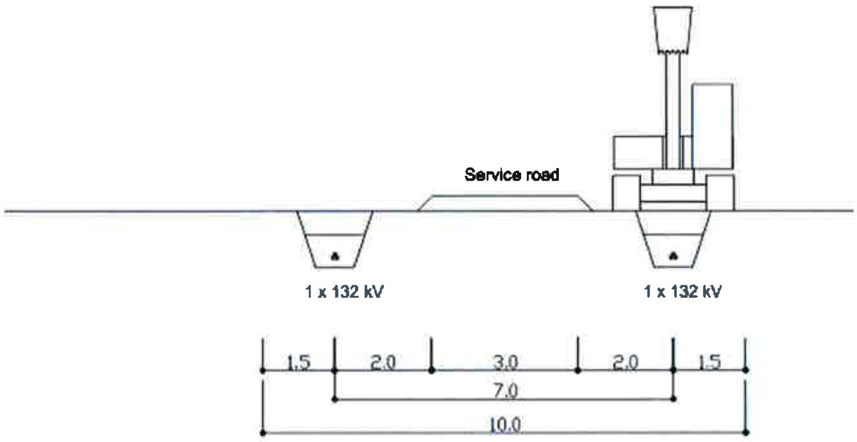

Figure 3-21. Minimum disturbance area for double set of 132 kV cables with service road between the two trenches. Excavated soil is removed from site.

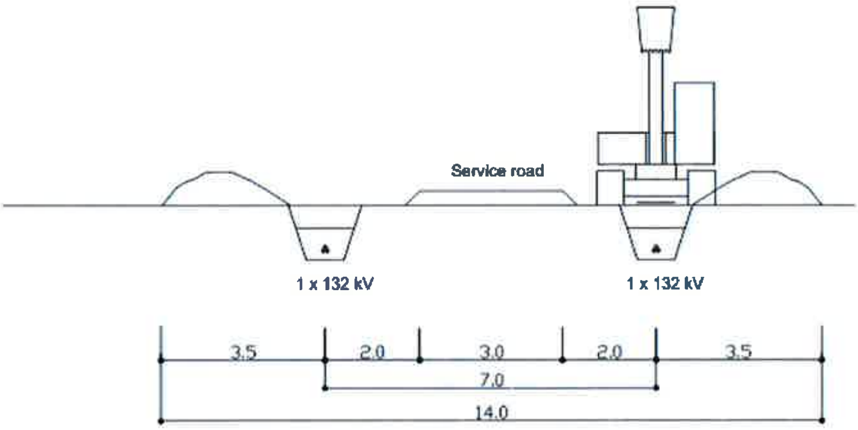

Figure 3-22. Maximum disturbance area for double set of 132 kV cables with service road between the two trenches. Excavated soil is placed beside the trench.

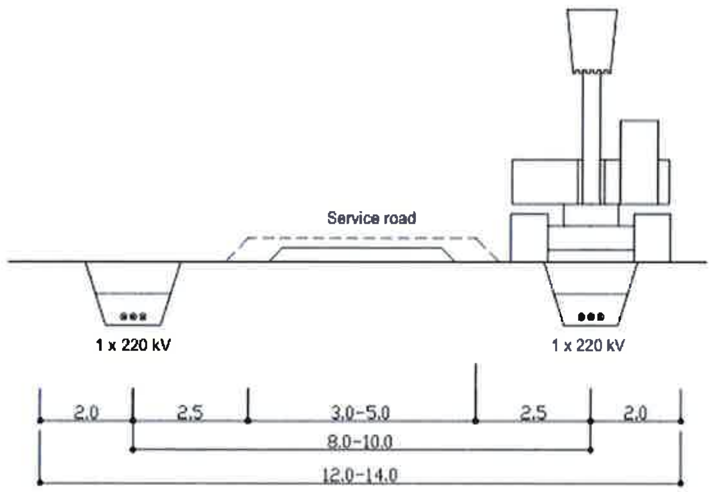

Figure 3-23. Minimum disturbance area for double set of 220 kV cables with service road between the two trenches. Excavated soil is removed from site.

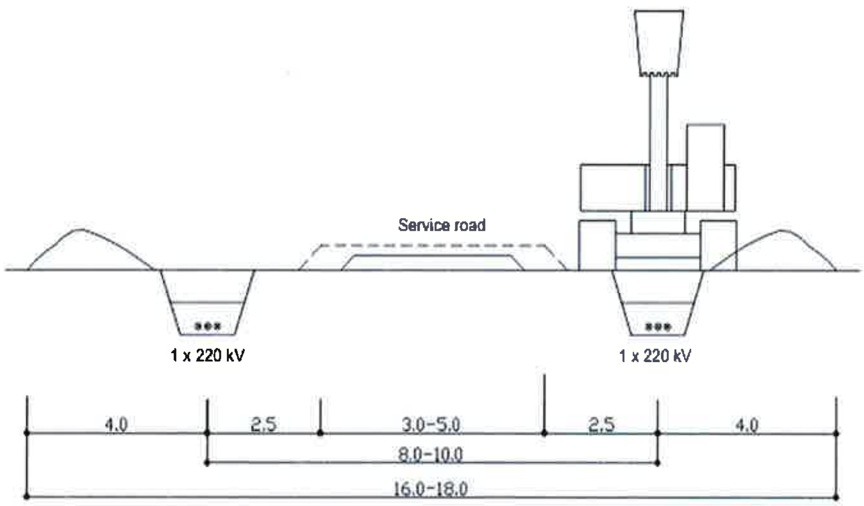

Figure 3-24. Maximum disturbance area for double set of 220 kV cables with service road between the two trenches. Excavated soil is placed beside the trench.

Table 3-1 shows numerical statistics about the disturbance area and amount of excavated material and thermal backfill material transported to site, according to the cross-section shown in the above figures.

Table 3-1. Size of disturbed areas and volume of excavated material and backfill based on examples of four different cross-sections for 132 kV and 220 kV cables, shown in figures 3.19 – 3.24.

Type of cross - section / Voltage	Disturbed area Total $[m^2/m]$		Service Road $[m^2/m]$		Cable Trench surface $[m^2/m]$		Thermal Backfill material $[m^3/m]$		Excavated material $[m^3/m]$	
	132 kV	220 KV	132 kV	220 kV	132 KV	220 kV	132 kV	220 kV	132 kV	220 kV
Min single	6.8	8.0	3.6	3.6	1.6	1.8	0.5	0.6	1.5	1.7
Max single	12.7	14.0	6.0	6.0	3.2	3.6	0.6	0.7	2.4	2.7
Min double	10.0	12.0	3.6	3.6	3.2	3.6	1.0	1.2	2.9	3.4
Max double	19.0	22.0	6.0	6.0	6.4	6.8	1.2	1.4	4.8	5.3

As stated above in text, figures and tables, the size of the disturbance area depends on the size of the cable, conditions at project site and installation methods. Disturbance area for a single set of cable varies from around 7,000 m^2/km (min 132 kV cable) to 14,000 m^2/km (max 220 kV cable). For a double set, the disturbance area varies from 10,000 m^2/km to 22,000 m^2/km. Excavated material varies from 1,500 m^3/km for a single set of 132 kV cable to 5,300 m^3/km for a double 220 kV set. Thermal backfill material, that in most cases will be transported to site from borrow areas in the vicinity, is between 500 m^3/km for a 132 kV single set to 1,400 m^3/km for a double set cable.

At connection points, a larger area will be disturbed (see chapter 3.7.1). An area for the cable drums is around 150 – 300 m^2, depending on the size of the drums, whose size in turn depends on the size of cable and the length on each drum. Distance between connection points is often 1 – 1.5 km. If the joint bays are located in a slope or where the landscape is uneven or rough, the area has to be levelled as much as possible before the joint bay is excavated. The use of steel plates (see discussion in chapter 3.6) where possible, instead of a traditional access road, would decrease the disrupted area both for the cable trench and the connection points. However, steel plates cannot be used if the cable route is in a slope as the plates would get slippery in rain and mud.

In natural areas, the surface can in some cases be fertilized to allow local vegetation to recover. However, many such sites will require further consideration as for example trees cannot be allowed to grow over a cable, so cable routes will be clearly visible in forested areas (see discussion in chapter 3.2.3). Lava areas can take a long time to recover especially if they are vegetated, i.e. with moss.

Figure 3-25. Surface finishing in different conditions, near Nesjavellir power plant and along the Nesjavallalína 2 cable.


Figure 3-26. Surface finishing in lava (water pipe) and in a totally different landscape in Europe.

As discussed in chapter 3.6, if the service roads remain, the possibility of accessing the cable for repair remains open, and they can also be used for other purposes as well. However, in some cases the service road needs to be removed or hidden in the landscape in the final phase of surface finishing.

The cable route is usually selected so that the distance and project cost between two joints in the main system are minimised. Many issues must be solved before the route is finally selected, such as unacceptable surface disruption. Previously disrupted areas can be a good choice, and in some cases they can be used at least partly. This was done for example for the Nesjavallalína 2 cable, which follows a previously made service road for the main hot water pipe from Nesjavellir to Reykjavík. Transport of electricity and transport of people does not always follow the same main routes and there can be different criteria in designing roads and cable routes.

3.10 Cable Backfill Materials

3.10.1 General

Thermal dissipation describes the properties of a material to transfer heat, and thermal resistance is the resistance of a material to transfer heat. Thermal dissipation and thermal resistance are reciprocal sizes. The unit for thermal conductivity is W/K*m and the unit for thermal resistance is K*m/W.

As mentioned in chapter 2.3.2, thermal dissipation of the soil surrounding underground cables is vital for the maintained service of the cable. Thermal conditions in Icelandic soil are widely unfavourable so detailed studies of Icelandic soil were performed for this research. It was also examined whether other solutions than the use of local materials were feasible. This study will be discussed in the following sections.

3.10.2 Factors Controlling Thermal Characteristics

Thermal characteristics of soils and aggregates are defined by several different factors or basic characteristics. Primary factors governing thermal resistivity of backfill materials are:

- Rock type and mineralogical composition
- Density (vesicular or porous vs. dense)
- Alteration
- Secondary minerals
- Grain size distribution (gradation)
- Grain shape and angularity

Some of those, mainly grain size and angularity, affect the following secondary or derivative factors that control much of the thermal dissipation of the soil:

- Compaction / consolidation
- Void volume and distribution
- Permeability
- Capillary effect (moisture retention)

The rock type, or petrographic composition, is important as the rock forming minerals can have very different thermal characteristics. In this context, the most important mineral is quartz, which is by far the most conductive mineral in common soils.

On a volcanic island like Iceland quite many rocks may be amorphous or glassy, that is without crystal structure, due to the rapid cooling of eruptive materials. Such materials normally have higher thermal resistivity than crystallized material.

Highly porous and vesicular rock fragments normally have higher thermal resistivity than dense rocks. The reason for this is that the vesicles or voids are filled with either air or water. Air has very high thermal resistivity, or more than tenfold that of the rocks themselves. Thermal resistivity of water is higher than for most minerals. As an example of this, pumice is widely used as an isolative construction component due to the high void ratio in its matrix.

The same applies for alteration; primary rock forming minerals tend to have lower thermal resistivity than common alteration minerals in highly altered rocks.

In soil and aggregate backfill, thermal dissipation is carried through surface contact areas and individual particles in the matrix, or by water in the voids. As mentioned earlier, fresh water does not have a good thermal conductivity. Nevertheless, the conductivity improves with the circulating effect of the water. Soil moisture also improves the contact between the soil particles, and the thermal resistivity usually increases dramatically when the hygroscopic water film surrounding the particles breaks down. This is what happens under thermal runaway conditions in the soil. Generally, the best soils are well graded, have low permeability, and high unit weight. The reason for this is the following: Low permeability results from low void ratio in the soil and therefore an increased contact area between individual particles. As the permeability in the soil is lower, the capillary effects are stronger. Strong capillary action increases the soil's ability to retain water. If a cable is located above the permanent ground water level in the percolation zone, the capillary capabilities of the surrounding soil becomes a very dominant factor in heat dissipation. Permeability and capillary effects are mainly controlled by the grain size distribution and, most importantly, the amount of fines. Fines are defined as particles <0.063 mm. A suitable amount of fines improves heat dissipation and reduces thermal resistivity in backfill material. The drawback in Iceland is that increased amount of fines leads to increased frost heave sensibility.

Densely packed or compacted soils dissipate heat better than loosely packed soil. This is due to the lower void volume and increasing contact between particles. Well graded soils, where smaller particles fill voids between the larger, have low thermal resistivity as the permeability is lower, and good compacting ability results in higher unit weight. The opposite is single size, poorly graded materials, which lead to poorer compaction, hence lower unit weight and higher void ratio. Single size materials have a lesser particle surface contact area, and again higher thermal resistivity. In figure 3-27 comparison for single sized material and recommended gradation boundary lines for cable backfill is shown.

Grain shape and angularity affect the compaction characteristics of the soil. Flaky and angular particles tend to give lesser compaction and unit weight.

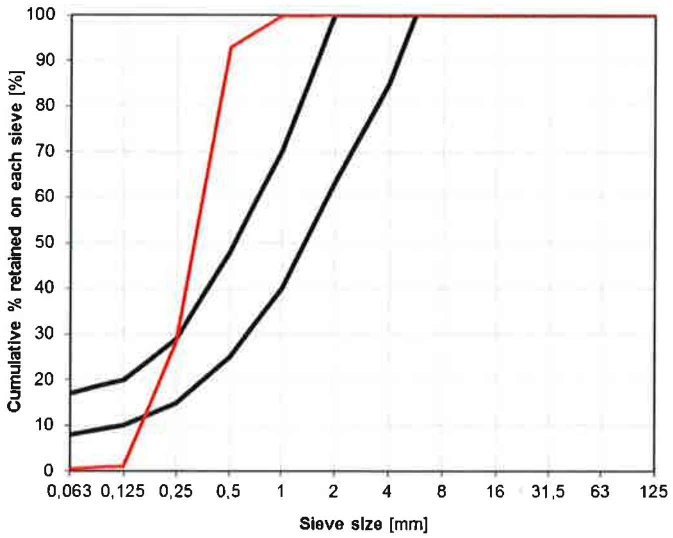

Figure 3-27. Grain size distribution for a single size material, shown with red line, in this case a beach tidal sand. The black lines are recommended gradation boundary lines for cable backfill, with suitable amount of fines.

3.10.3 Historical Introduction and the Importance of Thermal Properties

For the past decades, sand or aggregates in cable backfill in Iceland was regarded mainly as a mechanical protection against bruising and cutting by surrounding rocks at the ditch invert or walls, and protection from random stones in the re-used excavation materials. The selection of sand backfill was therefore based on local availability, cost and the workability of the sand by hand tools.

Most commonly sand resources were washed fluvial or tidal sands or produced sand from pillow lava quarries. Quite often such fluvial sands were poorly graded (single size gradation) and/or completely absent of fines. The other alternative, sand produced from the pillow lava, normally has a varying content of volcanic glass and vesicular fragments. It has a high friction angle, due to its roughness and high angularity, and reasonably good compaction characteristics, and as such is favoured by the construction industry. As explained above, glassy and vesicular fragments have higher thermal resistivity. Normal production of fill materials for the construction industry is mostly devoid of fines, due to frost heave sensitivity of such materials.

Thermal resistivity, permeability, capillary effects, and frost sensitivity are factors mainly controlled by the grain size distribution and, most importantly, the amount of fines (<0.063 mm). Increased amount of fines transposes to increased frost heave sensibility, which operators in quarries normally try to avoid. Sand with low thermal resistivity, or "a cable friendly sand" as such, has therefore not been readily available on the market and the production of such materials may appear to the contractors on the market as something new and unknown, hence it must include a risk factor for the contractors when bidding on cable projects. This has led to a large variation in unit prices for sand backfill for the few projects completed since Landsnet began to specify sand with proper gradation and suitable amount of fines. In some cases, the price variations can possibly be regarded as attempted tactical pricing, by bidding high on the sand and betting on the possibility of increased volumes during construction, thereby lifting the total payment.

Another drawback is that, even though suitable backfill material for cable projects is identified near a project area, the time restraints of planning procedure for new borrow areas and the negative public opinion against borrow areas often makes utilization of new areas or reopening of old ones not viable. Furthermore, almost all quarries in operation or open permitted borrow areas are located in formations that avoid materials with suitable fines content.

As such, it is very likely that in some cases the backfill material in use for cable projects is in fact with higher thermal resistivity than the native soil. As the current rating of underground cables is very dependent on the thermal dissipation to the surrounding soil, it is obviously very important to select and use backfill materials with low thermal resistivity.

For the past 10 years, there has been increasing awareness for the importance of the aggregate backfill characteristics in Iceland. Measurements of thermal characteristics of soil and fills started in 2007. Before that, a direct thermal measurement program was conducted on the 132 kV Nesjavallalína 1 cable. The understanding of this topic has increased since then.

3.10.4 Thermal Properties of Icelandic Soils

In situ measurements of thermal resistivity have been carried out since 2007 in Iceland. All measurements have been done for planned cable projects. The main focus of the thermal resistivity measurements has been on the backfill aggregates, but a total of 115 measurements have been carried out in the field on diverse cable routes. The results are shown in figure 3-28. The average value of the thermal resistivity for the whole data set is 1.53 K*m/W, with a standard deviation of 0.55.

Most of these include single point values, including a few with a questionably high standard deviation. Recent investigations for Hellulína 2 (HE2), Selfosslína 3 (SE3) and Akureyri have involved areas in fluvial or eolian sand formations. In these cases, samples have also been brought to the lab for controlled measurements at different moisture levels. The thermal resistivity of soil is highly dependent on the moisture content in the soil. Landsnet has therefore recently initiated a research program to measure native soil moisture in situ for a certain period.

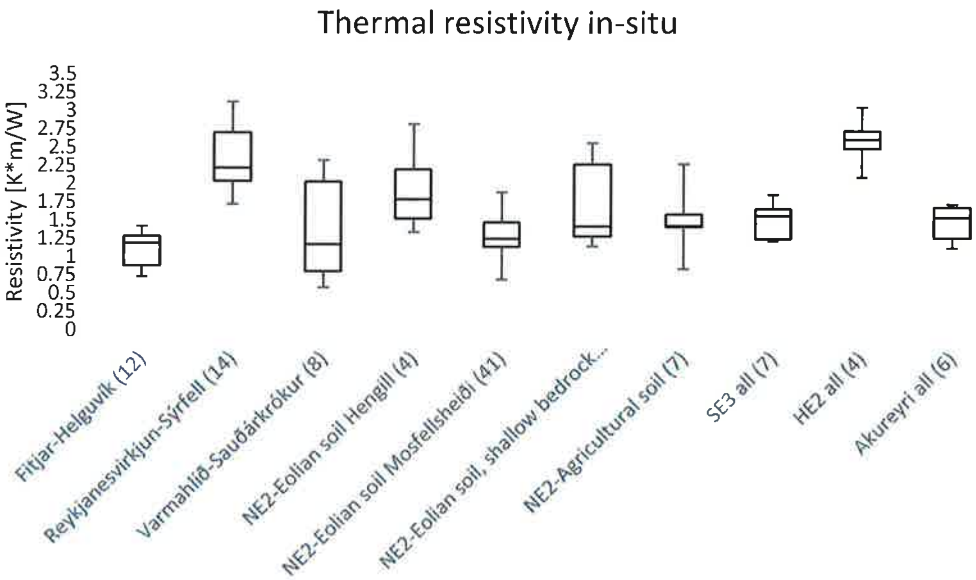

*Figure 3-28. In situ thermal resistivity for Icelandic cable projects. The boxes show median, 1st and 3 Quartile, the tick mark lines show absolute min and max values. Average value for the whole set is 1.53 K*m/W, standard deviation is 0.55.*

3.10.5 In Situ Moisture and Temperature Measurements

In the spring of 2014, Landsnet initiated a research program on in situ soil moisture and temperature. The measurement period will be two years at present and proposed cable routes in the southern and southwest parts of Iceland.

The objective is to estimate plausible soil moisture and temperature values for different in situ soil types.

The results will show the seasonal variation of in-situ water content and temperatures of different soil types. The measurements are performed at a depth of 0.8-1.0 m in fluvial or eolian sand formations, peat and backfill sand.

As part of this experiment, a 5 m long trench was excavated into a lava field close to the Hamranes substation. The trench was filled with backfill sand "ME-19" which is well graded 0-6 mm material.

The measurements started in June 2014. Weather conditions normally control the level of moisture and ground temperature. The summer and autumn of 2014 was exceptionally rainy, with the exception of a short drier period in August 2014.

Dry and hot summer periods are of most interest in this research program, as they resemble the most unfavourable conditions for underground cables. That is due to a higher risk of soil dry-out, and hence a higher thermal resistivity of the soil and increased ambient temperature.

Weather data is collected by the Icelandic Metrological Office at locations close to the sites. The observations from these weather stations will be used for interpretation of the ground measurements.

The following results from measurements carried out in the summer of 2014 are preliminary: The period was too short and the number of measurements too few to make reliable assumptions. However, measurements will be continued at least until the spring of 2016.

The water content measurements are volumetric based measurements. For geotechnical purposes, the water content is usually measured based on mass: References made to the

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moisture content of soil elsewhere in this report is always by mass (W_w/W_{sd}). The necessary volume/weight calibration remains to be applied to the results. The un-calibrated results can be seen in figure 3-29.

Figure 3-29. Measured volumetric water content, un-calibrated results.

The water content for in situ sand is measured in the range of 10% to 13%, for backfill sand in the range of 15.5% to 17.5%, and for peat in the range of 44.5% to 48.5%.

For measured in-situ density, the volumetric water content can be converted to water content based by mass correlation. Despite of the few measurements, the data shows the backfill's ability to retain water better than the in-situ sand. Direct mass based moisture measurements in other projects have shown a lowest value of 4.6% at 0.8 m depth for a single gradation sand formation by the end of June.

Figure 3-30 displays an example of soil temperature readings along with data gathered from the closest weather station for a particular site. The figure displays quite well the differences in ground temperatures based on soil types as the temperature in the sand rises higher than for the peat. For the same period the temperature in the backfill was significantly lower than the in-situ sand or ~8.5°C.

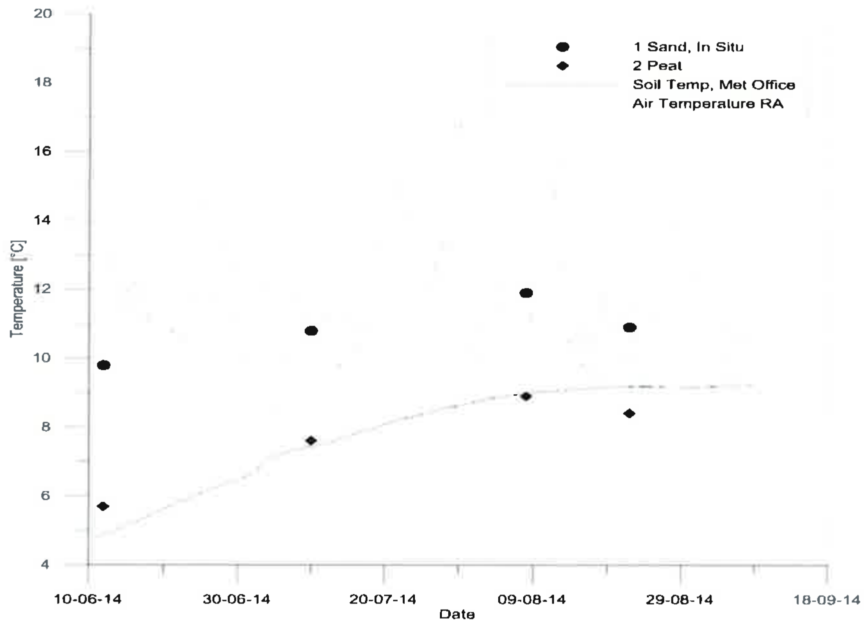

Figure 3-30. Measured temperature at sites 1 Sand, In Situ and 2 Peat.

Although these results are preliminary, they show the benefits of the backfill material versus in situ "single gradation" sands. The backfill retains the water better and does not respond as actively to the increased ambient summer temperature.

The single gradation sands reach a maximum summer temperature 12.4°C. Apparently, these formations respond quite quickly to droughts and increased air temperature. Thermal influx by solar radiation may also contribute significantly in this sense. Measurements of soil temperature on Sprengisandur in August 2014, showed soil temperature at 0.8 m depth at some 7.0°C at 800 m.a.s.l.[7] Measurement of groundwater temperature near Þorlákshöfn showed a temperature increase from 6.1°C to 8.1°C over a 24 day period in June 2014.

3.10.6 Thermal Properties of Icelandic Backfill Materials

Thermal resistivity measurements on material from borrow areas have been carried out in relation with various underground cable projects around Iceland. The areas are listed in table 3-2. As the thermal resistivity is directly dependent on the water content of the sample, a water content of 5 ± 1% was chosen as a representative value. That renders some of the measurements unfit for the comparison, as not all of the samples have been tested within that interval. The borrow areas not included are listed as well in table 3-2, but are not shown on the map in figure 3-31. The map shows the locations of the areas included in the statistical analysis carried out using the aforementioned values, and both existing and proposed underground cables. The borrow areas are colour coded on the map based on the thermal resistivity value measured at 5 ± 1% water content. The values available and used for the coding are listed in table 3-2.

[7] Meters above sea level.

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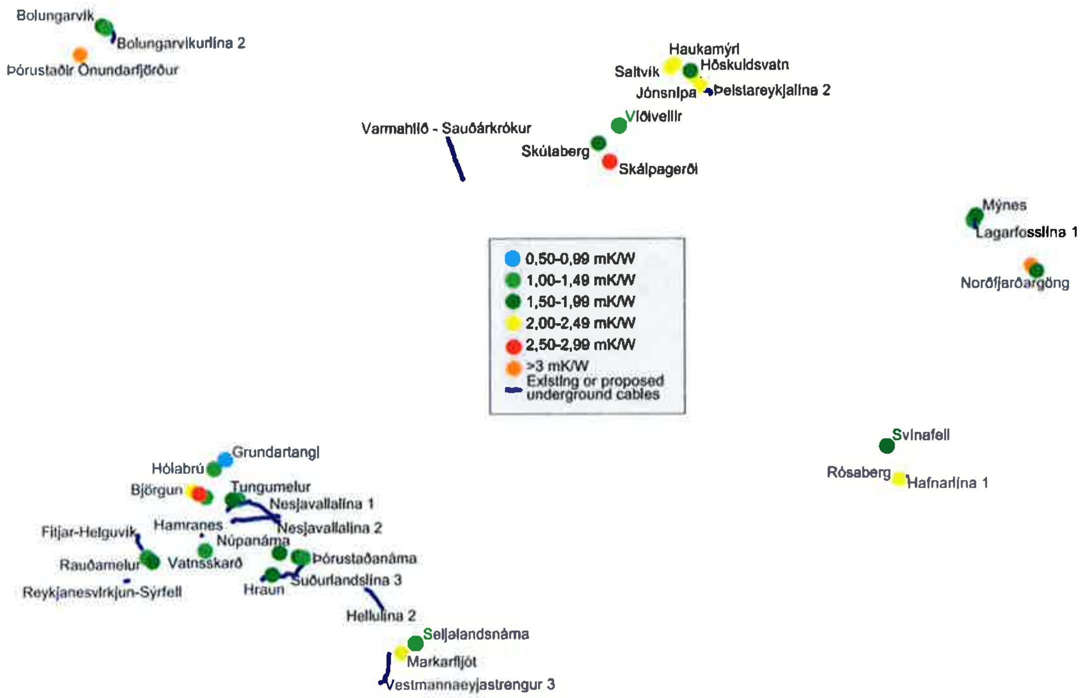

Figure 3-31.Geographical distribution of thermal resistivity measurements for borrow areas and underground cable projects.

The absolutely lowest values found so-far for natural sediment[8] are 1.1 – 1.2 K*m/W at 5% moisture level. Given the spread in the data one may not expect better values than 1.3 – 1.5 K*m/W for the backfill in a cable project. A comprehensive site-specific study of borrow areas would be necessary to yield better values.

The national average is 1.8 K*m/W, which is higher than for the in-situ measurements. That may be explained by the fact that quite many of the samples are lacking the before mentioned suitable amount of fines.

For comparison, thermal resistivity of 0.8 K*m/W is used as a reference value for Danish backfill material. Therefore, the capacity of equivalent cables would be around 30% higher in Denmark. It would be greatly beneficial if methods to improve thermal dissipation of the soil surrounding the cables in Iceland could be obtained.

A geographical analysis of the data set has not yielded a clear variation pattern that may be applied for generalized assumptions.

[8] The blue circle at Grundartangi is industrial waste from imported material. See discussion in chapter 3.11.2

Table 3-2. Borrow areas that have been tested regarding thermal resistivity at water content level (w.c.) of 5 ± 1%. No measurements at the right water content level were available in the areas listed as unfit.

Borrow area	Nr.	Type	Deposit	Project	Thermal resistivity at 5± 1% w.c.				Region/ average
Rauðamelur	16919	Sedimentary	Berm	General	1.44	1.85	1.93		Reykjanes Peninsula 1.53
Vatnsskarð	16878	Pillow basalt	Crushed rock	NE2	1.1	1.35			
Björgun	-	Sedimentary	Seafloor	General	1.3	2.41	3.37		Reykjavík area 1.64
Tungumelar	20437	Sedimentary	Stream terrace	NE2	1.27	1.5	1.63	1.7	
Hólabrú	19177	Sedimentary	Berm	NE2	1.11				
Grundartangi/ Elkem	-	Quartz	Industrial waste	General	0.48				
Þórustaðir Önundarfjörður	-	Sedimentary	Beach sand	General	2.67				West Fjords 1.78
Bolungarvík	-	Sedimentary	Beach sand	BV2	1.42	1.5	1.54		
Skútaberg	-	Igneous rock	Crushed rock	Akureyri	1.78				Northern Iceland 2.17
Skálpagerði	-	Sedimentary	Fluvial	Akureyri	3.61				
Víðivellir Fjóskadal	16065	Sedimentary	Fluvial	LA1	1.25				
Saltvík	19969	Sedimentary	Stream terrace	TR2	2.1	2.1			
Haukamýri	19970	Sedimentary	Stream terrace	TR2	2.35				
Höskuldsvatn	-	Sedimentary	Glacial	TR2	1.72	2.29			
Jónsnípa	-	Sedimentary	Eolian sand	TR2	2.27	2.27			
Mýnes	18598	Sedimentary	Fluvial	LF1	1.37	1.48	1.89		Eastern Iceland 1.88
Norðfjarðagöng	-	Bedrock	Crushed rock	Norðfjarðar-göng	2.81	1.59			
Rósaberg	-	Sedimentary	Fluvial	HA1	2.46				
Svínafell	-	Sedimentary	Fluvial	HA1	1.54				
Seljalandsheiði	22546	Igneous rock	Crushed rock	VM3	1.1				Southern Iceland 1.58
Markarfljót	-	Sedimentary	Fluvial	VM3/SE3	2.1				
Þórustaðanáma	15714	Sedimentary	Talus	VM3/SE3	1.23	1.58			
Núpanáma	16818	Sedimentary	Berm	SE3	1.72				
Hraun (fjara við Þorlákshöfn)	16599	Sedimentary	Eolian sand	SE3	1.74				
Areas unfit for statistical analysis									
Eyrarbakki/fjara	16598	Sedimentary	Beach sand	General					**National average 1.80**
Hvammsnáma	16807	Sedimentary	Glacio-fluvial	SE3					
Sandhjallar sunnan Skóga	18321	Sedimentary	Delta	LA1					
Hólasandsnáma	18470	Sedimentary	Esker	TR2					

In figure 3-32, a few examples of thermal resistivity for Icelandic backfill materials are presented to show the variation from reasonably good materials to poor materials. The lower cluster of lines represents many of the better materials in the data set. While the green line above shows typical properties for poor Icelandic materials. The sudden rise in resistivity at approx. 5% moisture level displays the “critical moisture” point. This represents the point where the capillary water film starts to disappear with a sudden increase in resistivity. Lower critical moisture level normally means that the material is less dependent on the soil water to dissipate the heat.

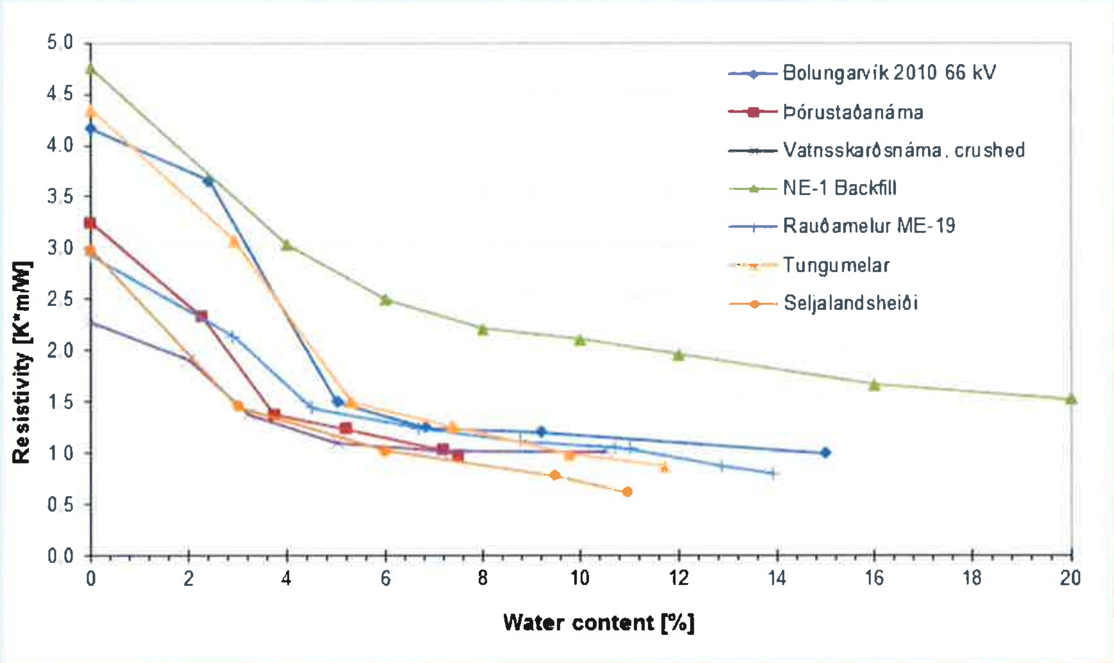

Figure 3-32. A few examples of thermal resistivity measurements for Icelandic backfill materials. The lower cluster represents the better materials, while the green line shows typical poor material.

3.11 Options to Improve Thermal Dissipation

3.11.1 Import of Backfill Material with Low Thermal Resistivity

For the past decades Iceland has imported large quantities of crushed gravel for asphalt production. The same applies in lesser extent to concrete production, with the exception of large scale projects, where large quantities of fill materials have been imported. It was therefore of interest to investigate if import of backfill aggregates with low thermal resistivity could be an economically viable option for underground cable projects in Iceland.

Such options would depend on the proximity of the project location to the nearest harbour facilities, and the relative size of the project. As for the material, it would only be low resistivity quartz products that could be considered.

The imported asphalt and concrete aggregates previously mentioned have mainly been from the west coast of Norway. The main import for the asphalt plants has been exceptionally competent quartz-diorite. In addition, the concrete plants have imported granite and gneiss products and to some extent quartz sand. Only pure quartz sand would be of interest in this context as the other minerals have higher thermal resistivity.

The Norwegian aggregate producers also provide pure quartz in various material sizes. It is generally expected that the price for the aggregates from a port in Norway would be rather similar for quartz compared with other bulk aggregates. The import prices derived from the

Icelandic companies can therefore be considered to be of the right order, as the transport and handling cost is most likely the dominant factor. [redacted]

[redacted]

[redacted] The imported sand is therefore, as expected, more expensive. As the thermal resistivity of such sand could be only 40 – 50% of the local sand, the cost of this option should be considered in context with choices of cable size and costs.

3.11.2 Local Quartz Resource – Recycling

One of the largest quartz aggregate producers in Norway is the Elkem plant in Tana, northern Norway. The factory produces high quality quartz aggregates for the ferrosilicium industry. Elkem also runs the ferrosilicium plant at Grundartangi in Hvalfjörður, West Iceland. Quartz is the main ingredients of ferrosilicon and the Grundartangi plant annually imports 220.000 tons of quartz aggregates from the Tana quarries.

Figure 3-33. A sample of the quartz from Elkem in Grundartanga Hvalfjörður.

The production line at Grundartangi is currently set up to use only aggregates larger than 12 mm. The whole bulk quartz is washed on a 13 mm screen before entering the smelter, producing a byproduct of material smaller than 12 mm. The annual amount of this 0 – 12 mm waste quartz has been some 6,000 – 7,000 tons per annum. This waste material has for the past decades been dumped as landfill in tidal pits at Grundartangi. Elkem is currently investigating possibilities to improve their production to allow smaller particles to enter the production line. However, even though such improvements were to be implemented in the future, there is still abundant waste quartz in the old tidal pits that can be recycled and used for cable sand.

The personnel at the Elkem plant has been very cooperative and provided samples of the material that is undergoing testing. The results so far have been very promising and the material is of good quality with thermal resistivity of 0.5 K*m/W at 3.8% moisture.

[redacted] equipped with an excavator capable of independent loading and unloading. Given two transport options, Helguvík on the Reykjanes peninsula and Akureyri in the north, [redacted] These numbers assume a rather low unit weight for bulk freight, comparing these numbers to compacted volumes in trench requires a minimum of additional 10 - 15% to compensate for different unit weights. [redacted]

The level of processing is uncertain as well and the transport cost has only been discussed with a single operator. Therefore, the numbers presented above have to be used with appropriate reservations.

3.11.3 Mixing quartz with local sands

As discussed previously, there is an abundance of waste quartz available at Grundartangi in Hvalfjörður. It is considered to be a viable option to mix this waste quartz, or other quartz products, with local sands available at project sites.

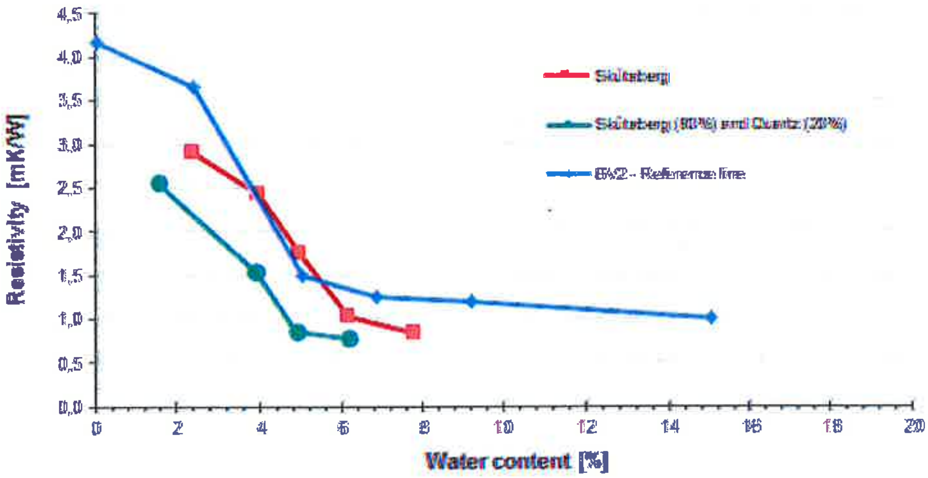

Figure 3-34. Thermal resistivity measurements for backfill material in Eyjafjörður (read line) and thermal resistivity of the same material after mixing 20% of quartz (green line). The blue line is a reference line that has been used in many 66 kV cable installation projects in Iceland.

Quite frequently, the "normal" production of Icelandic quarries has a low fraction of fines. Preliminary tests to investigate the possibilities of reducing the thermal resistivity of locally available sand by mixing it with quartz have been conducted. The experiment includes mixing the Skútaberg material from Akureyri with 20% quartz. The first results indicate that at least a proportional improvement may be expected at moisture levels above 6%. The improvement is more significant for the dryer part of the resistivity curve as the critical moisture points move from around 6% to approx. 4.7% and resistivity at 0.8 K*m/W, which represent a stable and good material by Icelandic standards.

3.11.4 Weak mix / Concrete

Weak mix is a terminology commonly used for low strength cast concrete. The concrete has to be weak so that later it can be broken from the cable, for inspections or repair, without damaging it. However, it must be said that weak mix has sometimes proven to be more difficult to break than it was supposed to. Concrete or weak mix is often used in urban areas to enhance thermal dissipation and as a mechanical protection for shallow cable placements. Furthermore, the weak mix prevents the material around the cable from dry-out – the 50°C boundary is moved to the surface of the weak mix as a limit during cable dimensioning (see chapter 2.3). If the cables are installed in ducts, normal concrete can in some cases be used instead of weak mix.

In 2009 weak mix concrete was designed and used for the first time in Iceland for the 132 kV Nesjavallalína 2 (NE2) project. The aggregates used in the mix were imported Danish sand and dense aggregates named "Hornafjarðarperla", transported from the southeast coast of Iceland. The thermal resistivity of the mix was measured lower than 0.8 K*m/W. Depending on the dry-out curve, this mix could show lower values, but conditions at the time did not allow the mix to be monitored sufficiently to confirm that. The mix recipe was developed and tested by Geotherm Inc. in cooperation with EFLA Consulting Engineers.

[redacted]

In the 132 kV NE2 project the mix was placed directly on the cable in a steep downhill slope in pillow lava breccia close to the Nesjavellir power plant.

The concrete or weak mix method offers rather stable conditions and good mechanical protection for cables. It is hardly viable as a main source of backfill for cables in Iceland, due to the transport distances for ready mix from batching plant and aggregates to the plant. Still, the experience with the weak mix is important as the method can be considered and used as special solution for crossings or in tight or completely drained conditions as well as for urban areas. For the vast lava fields it may be used to reduce excavation depths to the bare minimum, or to prevent erosion as was the case for the slope in the NE2 project.

3.11.5 Bentonite Mix

The 132 kV NE2 project involved directional drilling in bedrock, mainly palagonite formations such as pillow lava and tuff breccia. A total of 550 m were drilled in mixed conditions and with various results. The boreholes were 450 mm in diameter with three 160 mm PEH pipes for the conductors and a single 40 mm pipe for the optical fibre. The cable manufacturer required the borehole and the pipes to be fully grouted with thermal grout.

Approximately 90 tons of "Geothermal grout" from CETCO were imported and used. Such grouts are commonly a mix of fine quartz sand, bentonite and superplastisizers. The thermal resistivity is dependent on the water content of the mix and was measured at 0.52 – 0.62 K*m/W in the project. Grouting of the over 100 m long siphon boreholes required quite a large effort and skill, but did result in valuable lessons. Grouting of shorter pipes, as for highway crossings or similar, are considered far easier than the operations performed for the NE2 project.

Material import, transport, mixing, and pumping is currently estimated at a price level close to 100.000 ISK/ton of dry material, based on the experience from the NE2 project.

The use of specially designed thermal grout is therefore considered viable and recommended to improve thermal dissipation for special solutions.

The fractured bedrock at Nesjavellir required more grout than anticipated in the beginning. A home-made recipe of quartz sand, bentonite and cement was also developed and used in the project. The thermal resistivity of this particular mix was measured to be 0.65 – 0.74 K*m/W, slightly higher than for the special grout but well within the needed limits.

3.11.6 Silica Fume

Silica fume is normally used as admixture in concrete production, The Elkem factory at Grundartangi produces Silica fume as a by-product for the concrete industry. It is mineralogically amorphous silica, and since it is amorphous it does not have the same low thermal resistivity as crystalized quarts. An experiment which involved mixing silica fume with Icelandic sand, actually resulted in poorer thermal resistivity. The silica fume is also quite expensive and does not provide any improvement.

4 COST ESTIMATE

4.1 General

There are two types of cost estimates used in this study: Investment cost estimate and life-cycle cost estimate (LCC).

Investment cost estimate is a prediction of all costs associated with a project from beginning to energisation. It includes cost related to planning, design, permits, and construction as well as financial cost during the project's development.

Life-cycle cost estimate is an estimate of the total cost of ownership and operation, from inception to the end of the project's useful life and to final decommissioning and disposal. These costs include cost from investment, operation, maintenance, energy losses, repair due to failures, downtimes etc. Net present value (NPV) is used to bring all expenses of a project, over its entire useful life to a present day value that is then used for comparison with other alternatives. Life-cycle cost estimates are most pertinent during the decision-making phases of a project´s life. It is thus primarily a tool to determine the most cost-effective option among different competing alternative projects, when each is equally appropriate to be implemented on technical grounds.

In general, the early capital costs, particularly procurement and construction, are usually found to be the most significant for underground cable projects in LCC calculation. They are immediate and tend to be larger than later costs such as losses, operation, maintenance, repair, and dismantling, and hence have the greatest effect on the financing of projects. Costs during operation can be very difficult to estimate. It is particularly difficult to estimate both the magnitude and the cost of future electrical losses and possible cost due to outages.

The cost estimation in this study is based on the social cost approach. It means that it has a focus on the benefit of the society rather than the owner (grid operator). This approach influences the following cost issues:

- There is a 15% tax on cable material that the owner needs to pay. In this study it is ignored.
- The price of losses is based on marginal cost, i.e. representing the cost of supplying the next unit of energy required to cover the losses.
- Interest rates are based on rates typically used for public studies.

Interest rates used in a life-cycle cost estimation can be either real or current, in this case a real rate is assumed so that inflation does not need to be accounted for in the calculations. An interest rate of 5.5% is used in all the calculations. It can be argued that the choice of interest rate is not straightforward, so a sensitivity analysis can be recommended. For example an evaluation on the influence of using 2% higher and lower interest rates.

4.2 Cost Risk Approach

Cost estimation is a prediction of the probable expected final cost of a proposed project with a given scope of work. It needs to consider reasonable modification of the work scope based on the level of project definition (project stage) that is worked with. It is associated with uncertainty, and therefore is also associated with a probability of overrunning or underrunning the predicted cost.

Landsnet is using a cost risk assessment in the cost estimation process. The goal of the cost risk assessment is to capture uncertainty in cost methodology in order to move the deterministic point estimate to a probabilistic estimate. An individual cost element is described statistically with the triangular distribution. A credible baseline estimate is made from the available information; this estimate is defined as the most likely cost. An upper and lower bound on cost is then estimated with 90% probability of overrun (P10) and 10% probability of overrun (P90). The following figure demonstrates how cost element can be described statistically with the triangular distribution.

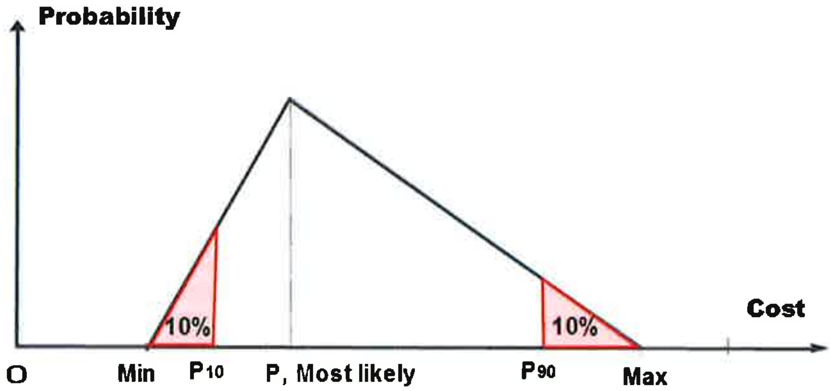

Figure 4-1. Cost estimate of individual cost element using 3 point estimate (P_{10}, P and P_{90}) and triangular distribution.

The distribution of an estimated project cost is obtained using a Monte Carlo simulation of all cost elements and considering the correlation between individual cost elements. Figure 4-2 shows an example of the distribution of overall project cost.

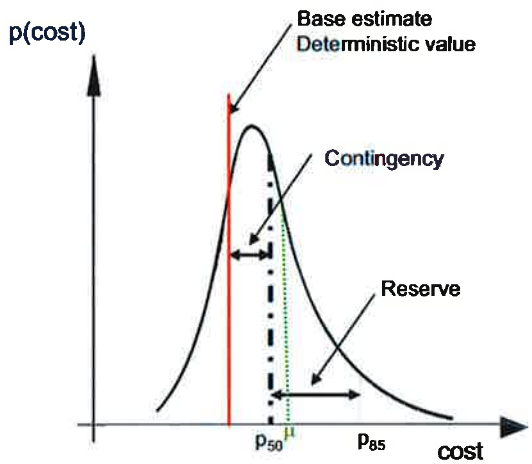

Figure 4-2. Distribution of overall project cost.

The base estimate is a sum of the most likely cost for each cost element. The median cost (P50) is usually higher than the base estimate since each cost element is most often skewed towards higher cost. The distribution of project cost is often reasonably described with a normal distribution: If the estimate is made with many cost elements, then the average cost (μ) is equal to the median cost.

Landsnet defines project budgets in the same way as many Nordic companies do, defining:

- Budged managed by the project manager = P_{50}
- Budget managed by the steering group = P_{85}
- Contingency = P_{50} – base estimate

Reserve = P_{85} – P_{50}

4.3 Project Scope Definition

The level of project definition has a large influence on the uncertainty of the cost estimation, since the cost range reduces as the project develops and becomes better defined. Each project has different phases, ranging from the initial ideas to the construction stage and later the project completion stage. For transmission systems the projects stages are often divided into:

- System analysis study stage.
- Pre-study stage (Feasibility)-Project design stage.
- Tender stage.
- Construction stage.
- Project completion stage.

Some of the main factors in a cable project that influence cost estimation and become more certain as project develops and when contracts are made are:

- Cable route and cable length.
- Transmission capacity and type of cable.
- Technical requirements.
- Need for reactive compensation.
- Crossings and special solutions.
- Soil conditions and availability of suitable backfill material.
- Access to work area.
- Time and duration of construction work.
- Requirements from environmental study.
- Agreements with landowners and interested parties.

4.4 Cables

The price for the cable is usually the largest cost item and thus one of the most important factors in the cost estimation. There are two main approaches to obtain a reliable estimate on cable cost in the early phase of a project:

(i) Based on prices supplied by cable manufacturers before the actual tendering process (budget price).
(ii) Based on actual cable prices in similar projects.

These prices represent the best information available at the time. But they may vary due to several factors, including:

- Market forces. Buying in a period of high demand will likely result in high prices.
- Quantities. Buying a few km of cable will likely result in higher unit prices than buying one hundred km of cables. There are fixed set up costs for manufacturing and construction that have to be paid irrespective of quantity ordered.
- Raw Materials. All raw material prices vary. Aluminium and copper have been particularly volatile recently. Variations in prices can be expected on all raw materials.
- Future business with the same client. A client that is expected to have many upcoming projects gets a better price, since contractors may want to reach a deal including upcoming projects.

There is a reasonable amount of manufacturers of underground cables, and in a study by Europacable (2011) it was expected that the cable production capacity would meet demands in Europe for the foreseeable future. In 2011 the annual capacity to produce, test, certify and install cables was estimated to be 700-1,000 km of single circuit 220 and/or 400 kV cables (2000-3000 phase km). If the demand for EHV XLPE cables were to increase beyond expectation, the industry is ready, as it has been in the past, to adapt the production capacity to meet new demand. Two to three years are necessary to build and qualify a new manufacturing line.

The contract with a cable manufacturer usually includes the items listed below:

- Cable material.
- Joints and terminations with accessories such as SVL, link boxes, link cable, grounding rods etc.
- Joint assembly work.
- Testing (routine test, type test, site testing etc.).

While the cable material is the dominant price item, the price of other items can also vary a lot between manufactures. Thus, when comparing prices, it is better to compare the overall price rather than the bare cable price alone.

There are several factors that affect the actual cable cost. The most important of these are the costs of conductor, sheath, and armour metals, the costs of insulation, sheathing, and semiconducting compounds, as well as other production related costs i.e. cost of equipment and labour. The single factor that describes the XLPE-Al cable cost reasonably between different voltages seems to be the overall cable weight.

Landsnet has regularly asked manufacturers for a budget price in order to make realistic cost estimations for cable projects. A cost base was made based on their replies; Figure 4-3 shows how the cost base has changed in the period from 2008-2013. The cost base is for relatively short cable sections, and here it includes joints and jointing work. The price of 66 kV cables is almost the same throughout the period, the price of 132 kV has reduced somewhat but the price of 220 kV has dropped significantly. The cable price of all voltage levels approaches a straight line fit between the cable weight and the price in 2013. This price development indicates that the price of 220 kV cables has now reached a more stable point in relation to the price of 66 kV and 132 kV cables.

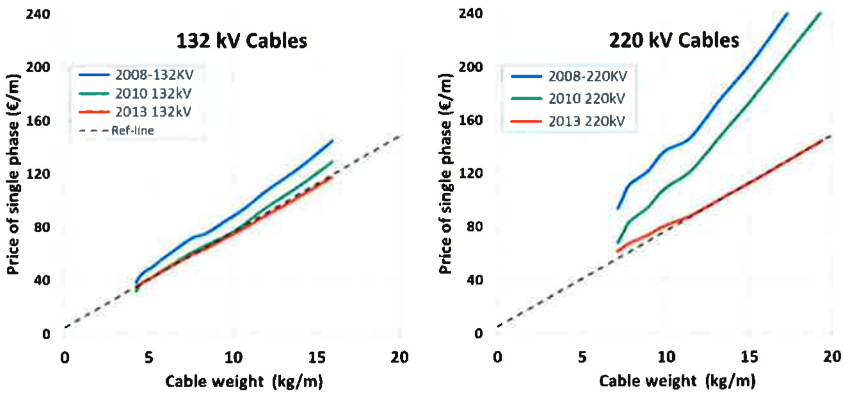

Figure 4-3. Estimation of cable prices in the period 2008-2013, budget price estimate. Price includes joints and jointing work for single XLPE-AL cables. Prices are based on budget prices obtained by Landsnet.

Budget prices on cables were given to Landsnet by three manufactures in the autumn 2013. Figure 4-4 shows how they varied between manufacturers based on voltage and cable weight. The budget price was for a small cable length, 5-20 km of single cable, and joints and jointing work is not included in these prices. Most of the prices fit reasonably well to a straight line fit, it is only the price of 132 kV cables from one manufacturer (Budget 1-132 kV) that is different and higher. Most of the prices were given for a stranded conductor but a few of the prices were for a Milliken conductor.

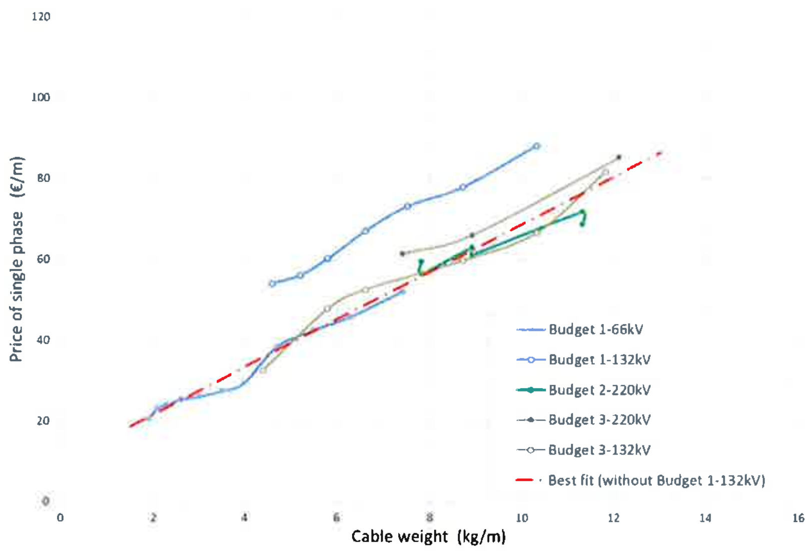

Figure 4-4. Budget prices given by three manufacturers in the autumn of 2013. Price includes single XLPE-Al cables (without joints) for an order size of 5-20 km of single cable.

Actual prices from contracts are usually more representative prices than budget prices. Figure 4-5 shows prices from actual contracts obtained in Iceland and Denmark in the period 2009-2014. The contract prices contain the whole cost relating to the manufacturer, including joints, joint assembly, transport, some cable testing etc. Some of the contracts have a cable length in the range of 75 - 180 km of single cable, and the voltage range is 66 – 220 kV. Reference lines from figure 4-3 and figure 4-4 are also presented in the figure. It may be seen that the budget price given by a manufacturer is somewhat higher than the actual price in contracts, especially considering that transport and some testing are also included in the contract prices. It is partly explained by different sizes of projects, but the largest part is most likely due to competition.

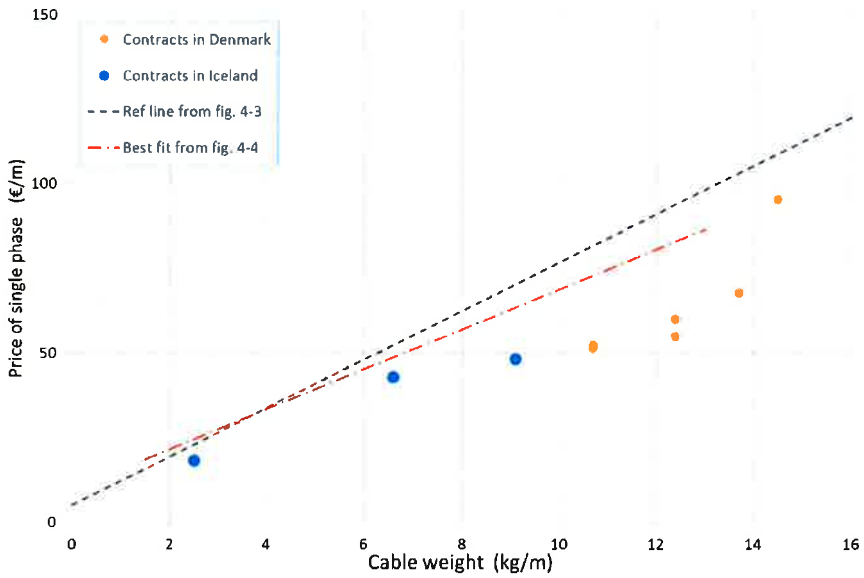

Figure 4-5. Cable prices for XLPE-AL cables from actual contracts (2009-2014). Including: cable, joints, joint assembly, transport, some cable testing etc. Reference lines from Figure 4-3 and Figure 4-4 are also presented.

Available data on cable cost from actual contracts and budget prices shows that cable price has been decreasing in the past few years, especially for the largest cables in the 220 kV and above category. This is partly due to improved technology, but also due to more competition in the cable manufacturing market where an increase in demand has been met with increased manufacturing capacity.

The cost of raw materials such as aluminium and copper influences the price of cable. The following figure shows how it has varied in the period from 2004 to 2014. As shown, there has been a large variation in the price, especially for copper.

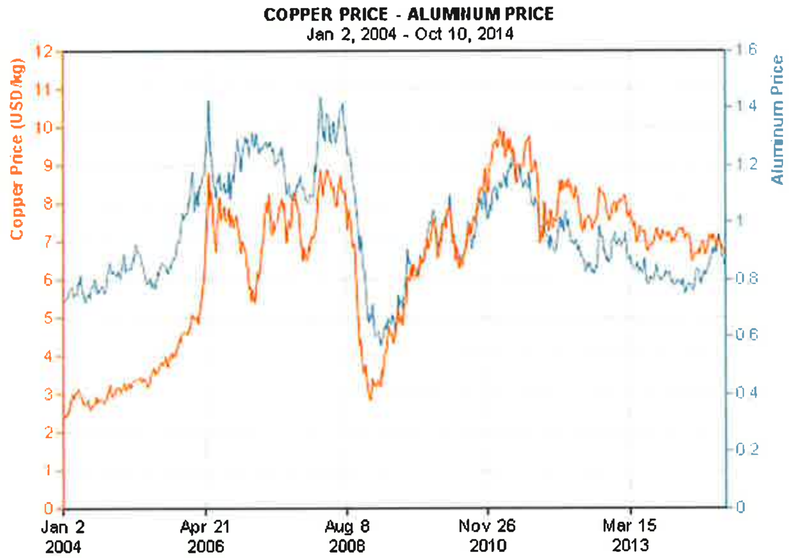

Figure 4-6. Variation in price of raw material of aluminium and copper in the period 2004-2014.

Cable contracts are usually made in euros. Cost estimation in Icelandic krona (ISK) therefore needs to consider the variation in currency exchange. Figure 4-7 shows the variation of the exchange rate in the period Jan. 2010 to Oct. 2014. It shows that the current exchange rate is favourable for the ISK, and the average value over the past years is close to 160 ISK for 1€.

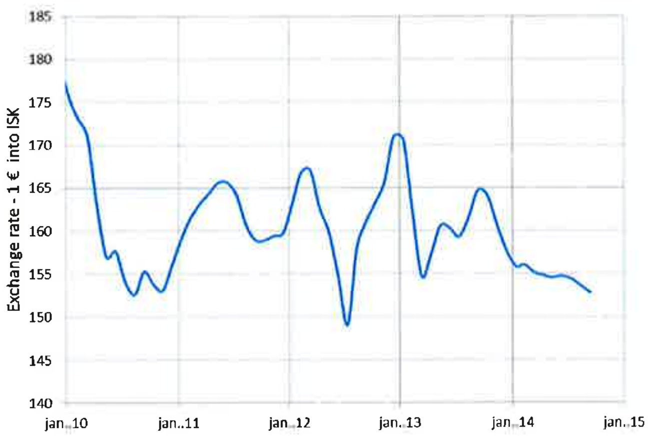

Figure 4-7. Exchange rate between € and ISK in the period Jan. 2010 to Oct. 2014.

Cost of jointing (material and assembly work) often varies considerably between manufactures and between tenders. There is a clear benefit in increasing the length between joints as the cost reduces and the failure rate is related to number of joints. The following figure shows the typical influence of joints on total cost, the values show a cost range often seen in tenders.

The length between joints in 220 kV is often in range of 750 – 1,250 m and the influence of the cable joint, including jointing work, is then typically in the range of 11-23% in addition to the price of the bare cable, although it can be both higher and lower.

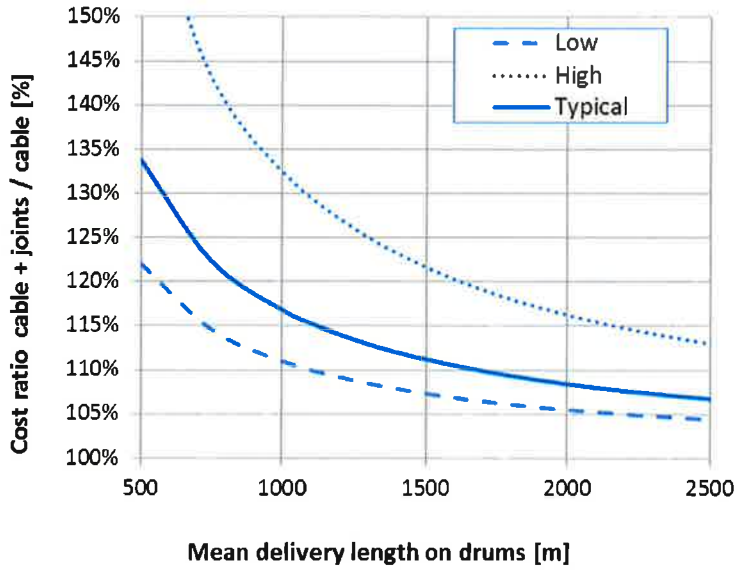

Figure 4-8. Typical influence of jointing cost (material and assembly work) in relation to bare cable cost. Cable terminations are not included.

It is reasonable to assume that the unit price of cable is related to the size of the order, due to cost reductions that are achieved through economies of scale, i.e. more continuity of the production line, reduced ordering cost and reduced testing and inspection costs.

4.5 Cable Installation

Putting the cables underground is a significant part of the cost of a project. The cost varies considerably depending on several factors.

In urban areas, the costs of cable installation tend to be significantly higher than in the countryside. In the city, there are likely to be a large number of crossing to be passed, for example roads, water pipes, and telecommunications lines. Future plans for buildings and roads can also restrict the cable route and the installation method. Crossings and restrictions generally lead to additional cost.

In rural or open areas, the costs of cable installation are likely to be less than in urban areas. Installation is usually made in an open trench. There are a number of factors that can influence the cost such as: (i) rock that has to be removed in the cable route, (ii) access to suitable backfill material, (iii) special crossings, ex. river crossings (iv) need for service road, (v) requirements to remove the service road after construction, (vi) requirements to remove extra material from excavation, (vii) requirements of surface finishing after installation.

There may be significant additional costs with large-scale rural undergrounding in order to preserve the natural environment. Special techniques such as directional drilling are also used for crossings under roads, in rock and waterways.

Figure 4-9 shows the typical range of installation cost that can be expected for cable installation in Iceland. It is based on the installation of a single set of cables in an open trench. The cost varies due to site conditions, project size, and project requirement.

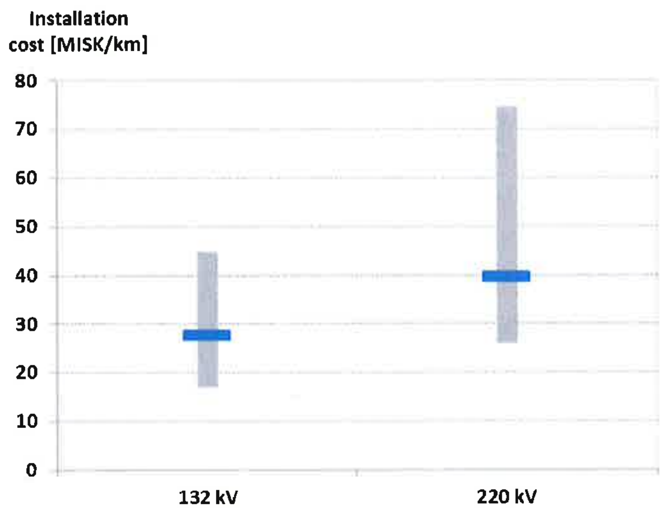

Figure 4-9. Typical cost range for cable installation in Iceland, average cost marked with blue line. Single set of cable, prices without VAT.

4.6 Preparation and Permits Cost

Preparation cost consists of work on the initial route selection, the setting of design parameters, and pre-design. All underground cables with voltage of 66 kV and higher, which also exceed the length of 10 km, have to undergo an environmental screening process, where the environmental authority (the National Planning Agency) decides whether a full scale EIA is needed or not. This work is included in the preparation costs.

Permit cost consist of planning issues, permits, and landowner licenses and compensation. The Icelandic Planning Act requires that underground cables on the voltages of 132 kV and 220 kV are accounted for in both municipal plans and also in detailed local plans if the cable route passes through areas where such plans are already in place. Furthermore, a permit from the energy authority and a construction permit from the municipality have to be acquired. In some cases, an environmental permit is also necessary, issued by the local health authorities. A license from relevant landowners is a precondition to a construction permit, and this license usually involves paying compensation to the affected persons.

Experience indicates that the cost of preparation and permits are often around 5 to 8% of the total project cost.

4.7 Design, Supervision and Managing Cost

This cost item includes the design phase, tendering phase, contracting, and all supervision with work and managing of the project. The cost design, supervision and management is often in range of 7 to 12% of the project cost, depending on the complication of the work and the size of the project.

4.8 Losses

Transmission line losses occur due to the flow of current through the conductor and the presence of voltage across the insulation. Power losses and energy losses in relation to cables, i.e. resistive losses, dielectric losses, shield losses, and reactive compensation losses are discussed in chapter 2.

When looking at investments in the infrastructure of society, it is often viewed from the society's point of view rather than the operational outcomes of utilities. It is therefore natural to look at the marginal cost of electricity supply every time when evaluating the unit cost of losses. In recent years, the electricity prices have been low in wholesale in Iceland, but in the fall of 2013 the price increased and is around 3.5 ISK/kWh for new contracts in the year 2014. In the long term the cost of electricity supply can be expected to rise since the more economic alternatives are used first for power production. Therefore, it can be assumed that energy price estimated in this way will increase.

The transmission losses in Landsnet's system were 340 GWh in 2012, and usage time of the transmission losses was over 6,100 hours. For such a user, the marginal cost of hydroelectric power facilities should now be around 3.3 ISK/kWh, which is in line with energy prices available in the Icelandic market. Cost of new geothermal power plants is probably somewhat higher than hydroelectric stations, or around or above 4 ISK/kWh especially considering that the Icelandic Master Plan for conservation of nature and utilization of energy (is. rammaáætlun) is now mainly considering geothermal stations as potential power projects. When most of the allowable hydropower and geothermal power development has been utilized, then it is likely that wind power will be the best alternative energy in combination with hydropower. The cost of energy in such circumstances could be about 6 ISK/kWh.

If the cost of losses is assessed based on the marginal cost of power generation, then it can be assumed to start at 3.5 ISK/kWh and rise yearly by 2.5% yearly until it reaches 6 ISK/kWh. It is not expected to exceed 6 ISK/kWh.

4.9 Operation, Maintenance and Failure Cost

The operational cost of a cable needs to consider its share in the overall operational cost of the whole grid and operation of the grid owner. It can be argued that the cost share shall partly be shared in relation to energy transfer and partly in relation to investment cost.

Once in operation, the cable system itself is nearly maintenance free. Regular maintenance includes: Regular inspection of the cable route and inspection of third parties working close to the cable route; inspection and control of the thermal condition of cable; training of specialists to deal with failures; operating stock with spare parts; checking and cleaning of terminations, inspections of SVL's, grounding systems etc.

Failures do occur in all systems, and often cable damage is the result of third-party activity. The cost of failures both includes the cost of repairing the failure and the cost cue to unavailability. Repair times for faults on cables, joints and terminations, will most often take between 7 and 19 days, but can take up to 2 months depending on the technology and location of the fault. The shorter repair time assumes that: (i) the cable jointing technicians are immediately available from overseas, (ii) that spare parts are immediately available, (iii) the site is accessible, and (iv) the fault is easily located. The effect of a long cable repair time on grid security may need to be considered. It can be mitigated by the provision of a spare cable per circuit or a spare circuit, but that is a costly alternative.

A detailed and reliable cost for operation, maintenance, and failure is unavailable. In this study it will be assumed that yearly cost of these items is 0.5% of the investment cost.

4.10 End of Life Cost, Dismantling

A comprehensive analysis of a transmission line project must take into account the end of life, i.e. the dismantling phase of the line. This operation foresees some costs in order to restore the environment at the end of line life, with a considerable delay with respect to the investment and a subsequent lower burden.

A cable system is usually assumed to have a design life of 40 years. Cables are usually provided with a manufacturer warranty for 2 to 3 years but can be up to 5 years. Some manufacturers claim that cables can last longer than 40 years, but today there is limited operational experience of XLPE cable that could covers such a long period. Components such as the joints and cable sealing ends are normally replaced after 40 years.

When XLPE cables reach their end of life, the following options are available:

- Leave the cable in the ground.
- Remove the cable.
- Reduce the operating voltage level to extend the cable system's service life.

Until now it has usually been assumed that the XLPE cables can be left intact in the ground after the end-of-life. It has been argued that there is a high cost involved in removing the cable and that it will be difficult and costly to restore the surface. The materials in a large conductor EHV cable system are not biodegradable, and there is a growing awareness that it may be negative to leave cables in the ground and that they should therefore be removed. In order to completely remove buried cables from the ground, a similar process must be undertaken as for the installation, and it might well need a temporary road construction. If, however, the cables are installed in air-filled ducts, the cable may be withdrawn from the ducts at their openings, without the need to excavate the entire length of trench.

Depending on the reason for the decommissioning of a cable circuit, the cable system may be capable of operating at a lower voltage level, e.g. 132 kV or 11 kV. Not every circuit would necessarily be in the correct position to be useful when operating at a lower voltage, and there would be a number of practical difficulties associated with connecting the cable system to a lower voltage network, in particular any transition connections.

There is a large uncertainty in the actual end-of-life cost. It is proposed to assume that the end-of-life cost is 6% of the initial cost. This estimate is surely too low to cover a total replacement of cable, but it is a reasonable value considering the overall uncertainty.

4.11 Intangible Factors

In general, it is apparent that where land has already been developed for residential use or where development potential is very high, underground cables are the preferred option, having less visual impact even if there are higher capital costs. In most countries the process of getting environmental approvals to build an overhead line is typically 5 – 10 years, whereas the process of getting approval for the installation of underground cables may take a somewhat shorter time. This shorter time may, in some cases, be considered in the cost estimation resulting in a quicker return on the investment.

The capacity of a cable is usually determined by assuming that the future growth in electrical load is known. Experience shows that many lines are replaced or significantly altered before they reach the end of their physical life. This results from unforeseen future loads and the changing nature of electrical loads which vary as customers' needs change and as industries establish themselves, close or relocate. A cable that has reserve capacity compared to given assumption has a value of future option that may be considered as a cost benefit in a LCC analysis.

5 CASE STUDY

5.1 General

The cases selected for the research project were chosen with the aim to be internally different with respect to connection to the existing transmission grid and with respect to geographical and geological conditions, thereby delivering as much knowledge to Landsnet as possible. Also, the selected cases are at locations where public discussion has been extensive regarding the installation of underground cables instead of OHTL.

It must, however, be made clear, that the cases studied in this research project are not detailed designs for individual cable projects, but a study of one or few possible variants in each case, the purpose of which are to shed a light on different aspects that have to be taken into account when considering undergrounding parts of a transmission system.

In this project three cases have been studied.

Case I - Sprengisandur. Partial undergrounding of a 200 km 220 kV transmission line connecting the southern and northeast parts of Iceland over the highlands (Sprengisandur). Different lengths of undergrounding were studied to identify the most realistic and cost-effective length. In this project, the scenario of required transmission capacity of 400 MVA is used, which allows one set of cable. If required transmission power will increase with different scenarios a second cable set would be installed later.

Case II - Eyjafjörður. Partial undergrounding of a 90 km long 220 kV transmission line between Akureyri and Krafla in northern Iceland. The case of inserting a 12 km long cable from Kífsá substation in the town of Akureyri, across a woodland area, an airport and a river, was analysed. The required transmission capacity for future use is 600 MVA, which requires two sets of Al cable or one set of Cu cable. For the security of the main transmission grid, both Al sets would have to be installed right from the start, or one extra (four altogether) Cu conductor. An alternative would be to use the 132 kV OHTL Kröflulína 1, as an alternative route the first years in case of a fault on the cable and a second set of cable would be installed later. All these alternatives are studied in chapter 5.4, in addition to three different cable routes.

Case III – Hafnarfjörður. Partial undergrounding of a 30 km long Suðurnesjalína 2. The case that was studied was the undergrounding of the first 1.5 km from the Hamranes substation. This analysis involves installing cable in the lava environment in the Reykjanes area. Required transmission capacity for future use is 600 MVA, but depending on development of load and production in the region, 300 MVA is considered to meet the transmission requirements in the beginning. The transmission system in Hafnarfjörður is much stronger and has more alternative routes than in Eyjafjörður, so an extra set of cables is not needed for security reasons. Therefore, in this project, a cable set with transmission capacity of 300 MVA is studied.

The case study for Case I - Sprengisandur is in chapter 5.2, case II - Eyjafjörður in chapter 5.4 and Case III - Hafnarfjörður in chapter 5.6.

5.2 Case I - SPRENGISANDUR

5.2.1 Detailed Description

The case study presented here involves the establishment of a link between the southern part of the Icelandic transmission system and the northern one, through the highlands across the Sprengisandur area. Undergrounding a part of this link, crossing the central highland, is the main focus of the study.

In this case the issue of a single or double set of underground cables is of relevance. A second cable set may need to be installed at a later time, i.e. when the transmission requirements call for it. In the meantime, with just a single set, the transmission system will have to rely on the circular connected line around Iceland for back-up.

It must be emphasised that the purpose of this case study description is not to give a detailed description of the project design.

A simplified drawing of the setup is shown in figure 5-1. Where OHTL is the proposed overhead transmission line and UGC is the underground cable. The four different scenarios that where analysed to determine the maximum possible length of an underground cable in Sprengisandur are shown in table 5-1.

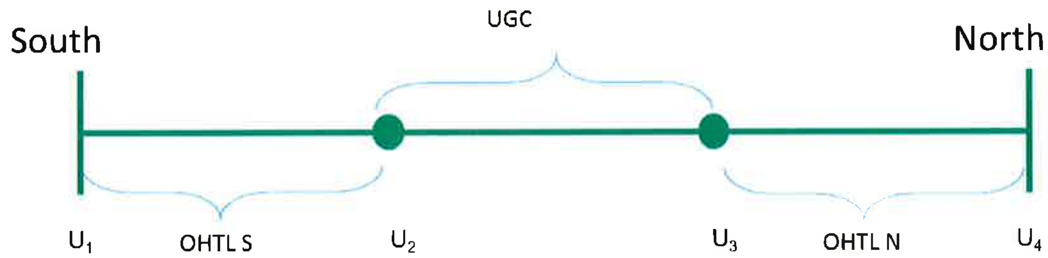

Figure 5-1. A simplified drawing of the proposed south-north connection.

Table 5-1. The four different scenarios for Sprengisandslína that have been analysed to determine the maximum possible length of an underground cable from a transmission system perspective.

Scenario	Length of southern overhead section OHTL S (km)	Length of underground cable section UGC (km)	Length of northern overhead section OHTL N (km)	Total length of north-south connection (km)
1	82.5	25	92.5	200
2	63.7	53.6	79	196.3
3	63.7	66.2	66.8	196.7
4	57.5	75	67.5	200

The purpose of analysing these scenarios is to build a foundation for being able to assess the maximum possible length of the cable section from the transmission system perspective. This assessment is a kind of an iterative process. The approach is pursued in chapter 5.2.4.

5.2.2 General conditions on cable route

The proposed transmission line, Sprengisandslína, will traverse the central highland of Iceland between Hofsjökull and Vatnajökull glaciers, from the Búrfell area in the south towards

Bárðardalur valley in the north. The proposed cable route lies between 640 and 840 m.a.s.l. The average yearly temperature at Sandbúðir, close to the northern end of the proposed cable is -1.6°C for the period 1993 – 2010, the average for June, July and August is 6.2°C. The warmest week in that observation period averaged 13.1°C, but daily values can be well above 20°C.

Sprengisandur is an old route that has been used for centuries. The current road across Sprengisandur is defined as a mountain road or a track; in essence it is a dozer track, as it is not built up. The road is normally open for traffic 3 - 4 months a year. That fact, along with the harsh weather conditions in the area, sets significant restrains on the construction period for an underground cable. The same would apply in general for overhead transmission lines (OHTL), but such a project would allow for a slightly longer construction period.

Landsnet has carried out several studies in this area over the past decades, mainly inclined towards OHTL. A fibre optic cable was laid across the area in 2001 and currently the road administration is studying the building of a new proper road through the area. In this cable study a cable route that follows a combination of the old Sprengisandur track and the fibre optic route is selected. There are several options available for cable routes, but on average these options would be quite similar in terms of earthworks.

The landscape can be described as rolling or hummocky hills with vast sand plains. The landscape is rather gentle, as there are no steep hillsides or deep ravines to be crossed. The vegetation cover on the proposed route is sparse or almost non-existent. The surface is generally a very thin cover of gravel over eolian sand. The gravel cover may therefore be rather misleading at first glance. The eolian sand is 0.2 to > 1.0 m thick. Under the sand are most frequently moraine deposits in varying thickness. Fluvial deposits are also quite common. The bedrock is a combination of "moberg" which is a hyaloclastic formation of tuff, tuff breccia and ancient basalt lava flows.

Sprengisandur follows the volcanic zone and that affects the sand and the gravel qualities. The eolian sand is expected to have rather poor thermal resistivity, while the underlying moraine should be fair, given Icelandic conditions. The excavation conditions should in general be fair. However, it can be expected that the moraine will gradually be more consolidated with increasing depth. The before mentioned optical fibre cable was ploughed down via this route to a level of 0.7 m. During the laying of the optical cable, a bulldozer with a ripper needed to pre-plough through quite extensive areas. The current estimate for solid excavation is 5% of the route, but this estimate may be too low, given the trench depth of ~ 1.3 m. Each 10 cm increase or decrease in excavation depth will affect the solid excavation quantities greatly as the consolidation of the deposits starts to increase significantly at ~0.8 m depth.

With -1.6°C in average yearly temperature, the area can be defined as sporadic permafrost area. The permafrost is confined to areas with significant vegetation cover, due to the isolating effects of the vegetation cover, and to areas with limited solar radiation (shadow areas). Such conditions were not detected on the cable route. In August 2014, the temperature was measured at 6.2 to 7.8°C at 0.5 to 0.8 m depth in the ground. Interestingly, the higher temperatures were in the northern part, despite of being higher above sea level: More solar radiation resulted in higher ground temperature at that point. The moisture content of the soil, at the same time and depth, was in general between 7.8 – 15.6%.

Fluvial deposits are found in many areas that are suitable for construction track materials. For the purposes of the cost estimate, it is assumed that borrow areas for thermal backfill can be found within the area and that permission would be granted to allow such use.

Figure 5-2. Case I – Sprengisandur. The cable route is shown in a red dashed line. The red continuous line shows the proposed overhead transmission line. A larger map is in Appendix A.

Table 5-2. General conditions on the cable route at Sprengisandur

	Mean	Max (worst case)
Thermal Resistance: in situ [K*m/W]	1.50	2.50
Thermal Resistance: sand (Local) [K*m/W}	1.50	
Air Temp (annual mean) [°C]	-1.6°C	
Air Temp (summer weekly mean) [°C]	6.2°C	13.1°C
Air Temp typical selected value [°C]	5°C	
Conditions	Moraine, sand & gravel, weathering soil	

5.2.3 Prerequisites

The approach used for this case was to pin down some basic prerequisites and conduct calculations to check if certain cable lengths could be applied for this line within reasonable restrictions. The criteria that have to be checked are already described in chapter 2

The basic prerequisites are:

- Total length is approximately 200 km (i.e. OHTL – UGC – OHTL as shown in figure 5-1).
- Required transmission is S_n = 400 MVA apparent power and nominal active power P_n = 300 MW. A second cable set with the same transmission capacity will eventually be installed at a later stage.

- Installation depth is 1.1 m. Trench depth is 1.2 m and bottom width is 1.0 m. The first 0.1 m is filled with thermal backfill material. Total thermal backfill height is 0.5 m (measured from trench bottom).
- Air- and soil temperature is 5°C.
- Thermal resistance of the surrounding soil is 1.5 K*m/W (mean value).
- Basic backfill material has a thermal resistance of 1.5 K*m/W, but quartz material with 0.6 K*m/W transferred from West Iceland (see chapter 3.11.2) can be applied as an alternative. Due to the long transport distance and cable length, it is however not considered to be realistic to apply this material in the Sprengisandur case.
- Laying formation in flat formation, with (120+D) mm between cable centers.
- Screens are cross bonded.
- Allowed continuous temperature on the cable outer sheath is 50°C. This corresponds to a calculated conductor temperature of approximately 65°C.
- Power quality shall be according to the parliamentary regulation no. 1048/2004. This defines voltage peaks and dips, harmonic content and other items that will be affected by the cable section and the respective compensation equipment.
- System voltage on the transmission line, including underground cable section, shall not exceed 1.1 pu at any point of the installation during operation
- According to the above parliamentary regulation no. 1048/2004, the voltage step caused by switching the cable section in or out is not to exceed 5%.
- The voltage set-points of nearby generators at the southern end can be controlled down to 0.9 pu. However, at this set-point value the voltage at the southern end of the Sprengisandur line will still be approximately 1.02 pu at the moment of energising the line
- At the time when the Sprengisandur line will be realised, it is uncertain if a 220 kV system will be present at the northern end of the line. Thus, the short circuit power will be 3700 MVA at the southern end and may be as low as 800 MVA at the northern end. After the connection of the Sprengisandur line, the northern end would then reach approximately 1000 MVA.
- Conductor temperature will be monitored continuously with an FO cable laid along the cable route.

5.2.4 Calculations and limits

Voltage criterion

As discussed in chapter 2, the voltage criterion defines the voltage rise due to the Ferranti effect. This is described by the following equation:

Equation 5-1

$$L_{crit} = \sqrt{\frac{2}{X' * B'}\left\{1 - \frac{1}{\Delta U}\right\}}$$

As described in chapter 2, the parameter ΔU is the difference between the voltages on each end of the cable section. The voltage upper limit (i.e. U_{max}) is 1.1 pu.

Current rating

In the following section, two variants of conductors and backfill materials are compared. The calculations are the results of a numerical analysis, where a typical cable with stranded Al conductors is modelled, along with the thermal backfill, excavated/competent backfill and surrounding native soil. An aluminium conductor with a segmental conductor design is modelled for comparison and selected as the base case. The results are shown in table 5-3 below.

The base case for Sprengisandur was defined with 3x1x2000 mm^2 Al cables with segmented conductors.

Two other configurations, designated as variant 2 and variant 3, are shown in the table for comparison, but neither can be considered for practical reasons. Variant 2, with normal simple stranded Al conductors, does not provide sufficient current capacity and variant 3, with quartz sand as thermal backfill material, cannot be considered due to high transport cost of the backfill material.

Table 5-3. Comparison of two variants of conductors and backfill materials.

Variant	Cable Type	Backfill th. Res. K*m/W	Backfill height mm	Conductor Temp °C	Current rating A	MVA
Base variant	3x1x2000q Al*	1.5	500	65	1,046	399
Variant 2	3x1x2000q Al	1.5	500	65	955	364
Variant 3	3x1x2000q Al*	0.6	500	65	1,183	451
*Segmental conductor						

Compensation requirements and critical length

The voltage criterion was applied to investigate how long the cable section can be, as this criterion is more stringent than the active power criterion, i.e. the critical length according to the voltage criterion is shorter than the critical length calculated by the active power criterion, as explained in chapter 2.5.2. The basic requirements are that the transmission link is energised from the southern end and that the voltage at the northern (open) end is not to exceed 1.1 pu. The reactive power produced by the cable increases the voltage along the cable route. The longer the cable, the more reactive power it produces and the higher the voltage rise is.

The main challenge in this context is to keep the voltage at the southern end as low as possible, albeit without jeopardising other sections of the system (for instance the underlying 66 kV transmission system in South Iceland). As shown in chapter 2 (figure 2-14) the voltage difference between the ends has a crucial impact on the critical length.

The voltage may be kept low by two means:

- Temporarily adjusting the voltage set-points of the nearby generators during the energisation of the cable.
- Installing reactors at the southern end.

For all the scenarios investigated here (listed in table 5-1), the set-points have been adjusted and a 50% no-load compensation applied. Table 5-4 summarises the results, with the voltages at points U_1, U_2, U_3 and U_4 in figure 5-1 shown.

Table 5-4. Results from applying the voltage criterion for estimating the critical length.

Scenario	Voltage				No-load reactive production (at 220 kV)	50% reactive compensation	Remarks
	U_1 (pu)	U_2 (pu)	U_3 (pu)	U_4 (pu)			
1	1.006	1.056	1.061	1.066	91.2 Mvar	45.6 Mvar	Apparently the 50% compensation is more than enough.
2	0.983	1.052	1.071	1.075	195.6 Mvar	97.8 Mvar	Apparently the 50% compensation is more than enough, or the voltage at the southern end does not need to be lowered so much.
3	0.992	1.077	1.106	1.109	241.6 Mvar	120.8 Mvar	This case is at or beyond the limit, i.e. the voltage criteria is at risk and the voltage in the underlying 66 kV system is very low.
4	1.000	1.087	1.125	1.128	273.6	136.8 Mvar	In this case the lowering of voltage set-points and 50% compensation are not enough.

These results are illustrated graphically in figure 5-3 below. In the figure, the operating points (red squares) from table 5-4 above are superimposed on the plot of figure 2-13 in chapter 2.5.1.

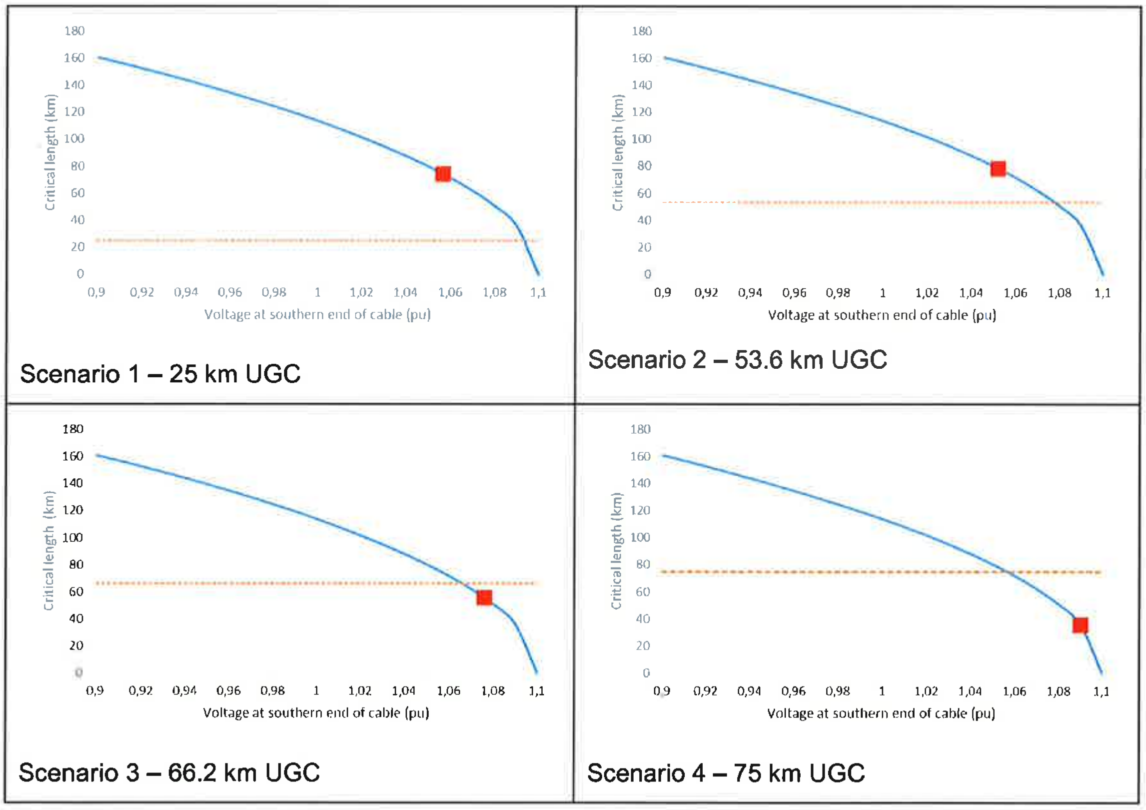

Figure 5-3. Graphical representation of the results from applying the voltage criterion.

Operating points lying above the orange dashed line indicate that the critical length (based on the voltage criterion) has not been reached. Values beneath the orange dashed line indicate that the length of the cable section is beyond the critical length.

These results imply that the absolute maximum length, given the above assumptions regarding compensation and adjustment of voltage set-points, is approximately 60 km. This may, however, be an overestimated value, since lowering the set-points this much as well as inserting a cable of that length will have a negative effect on the voltage regulating capabilities of the nearby generators. The reason for this is that the generators will be quite under-excited and hardly able to participate in the voltage regulation. One can see that even though the voltage set-points are adjusted down to 0.95 – 0.90 pu, the voltage at the southern point could become as high as 1.0 pu. This is due to the reactive power production of the cable section and the resulting voltage rise.

Given the prerequisites in chapter 5.2.3, the compensation requirements were calculated for the section length combination [Line-south; UG cable; Line-north] 63.7 km ; 60 km ; 73 km and the line compensated by 50% (118.5 Mvar). This is considered to be approximately the maximum length of the cable section, with respect to the total short circuit strength of the system, voltage limit restraints, and compensation requirements. However, this size of compensation might be a challenge for a system as weak as the Icelandic transmission system, thus a practical maximum might be closer to 50 km. By adjusting the voltage set-points, the voltage at the southern end of the cable can be lowered to 1.066 pu with the northern end open. This gives a critical length slightly over 60 km, as indicated in figure 5-4 below.

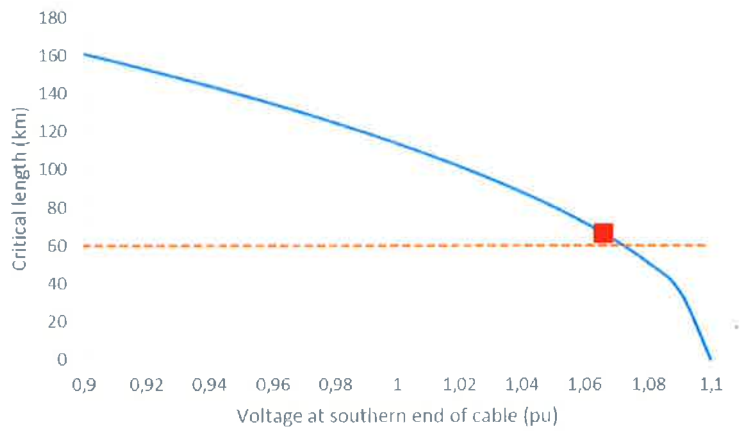

Figure 5-4. The operating point compared with critical length according to the voltage criterion. 50% compensation (118.5 Mvar).

When the line is in operation and the voltage set-points of the generating units are at normal levels, the 50% compensation is not enough. By adding a 50 Mvar reactor at the southern end, the voltage is below 1.1 pu. However, should the line trip when in normal operation, it must be ensured that it trips at both ends simultaneously to avoid excessive voltage rise along the line route.

As discussed in chapter 2.5.1 the short circuit capacity at the point of connection has great influence on the resonant frequency of the system. An underground cable of the length as proposed above, with a maximum length of 60 km, will produce nearly 240 Mvar of reactive power. This is an excessive amount of reactive power in a system where the maximum local short-circuit capacity is less than 4000 MVA in the south and even as low as 800 MVA in the north. Even with the proposed compensation (118.5 Mvar + 50 Mvar) the ratio is very low, resulting in a low resonant frequency, i.e. between the 3rd and 5th harmonics. These harmonics are present in the system and will be amplified in the connection points of the cable circuit, thus jeopardising the voltage quality for other transmission system users.

Reactive compensating units

The size of the reactive compensating units depends, to a certain degree, on the loading of the line. Low loading needs more compensation than high loading. The length of the cable section has a very significant impact on the necessary size. There is also a need for extra compensation when energising the circuit. Due to the difference in short-circuit capacity between the northern and southern systems, energising the circuit from the northern system will not be possible.

As pointed out in chapter 2.5.1, compensating more than 50% requires special attention when energising the cable. With normal operating voltage at the southern end, more compensation will be needed. This means that switchable reactors with tap-changers will most probably be needed.

The most effective placement of the reactors is at the cable ends. For the scenario with the shortest cable (25 km), load flow simulations show that the 50% compensation at the southern end is enough during normal operation and also during energisation, given that the voltage set-points of the generating units in the southern area can be lowered. For scenario 2, with a cable of 53.6 km, the 50% compensation is not enough for normal operation. Additional compensation of 30 Mvar is needed. For scenario 3 (66.2 km), an additional compensation of 60 Mvar is needed, and for the fourth scenario (75 km) additional 85 Mvar is needed.

These results are summarised in the table 5-5 below, together with the approximate maximum cable length case (50 km).

Table 5-5. Need for reactive compensation for the four different scenarios together with the maximum length case.

Scenario	Length of cable	Reactor size...	
		50% compensation	Additional compensation required for normal operation
1	25 km	45.6 Mvar	-
2	53.6 km	97.8 Mvar	30 Mvar
3	66.2 km	120.8 Mvar	60 Mvar
4	75 km	136.8 Mvar	85 Mvar
Max length	50 km	91 Mvar	40 Mvar

The load flow calculations do not show the need for compensating somewhere along the cable route. It may, however, be sensible to split up the large compensating units and place them at each end of the cable.

For practical reasons it is assumed that the reactive compensation units will be identical, i.e. one at each end of the Sprengisandur line, 40 – 80 MVA each, except for scenario 1 where one compensation unit would suffice.

The results above apply to a single cable set. Should another cable set, of the same length (i.e. 50 km) be installed at a later stage, a number of additional precautions must be taken. Both sets cannot be energised at the same time, thus circuit breakers will be needed at both ends of the second cable set. Also, more than doubling of the reactive compensation will be needed, and these compensating units have to be located at each end of the cable section. Thus, adding another cable set implies that a substation will have to be installed at each end, housing the circuit breakers and the additional reactive compensating units.

Two cable sets of the lengths investigated here (i.e. 25 km and more) will, at all times, need circuit breakers at both ends for at least one of the two cable sets.

5.2.5 Cable Installation

General

As mentioned earlier, the cable route lies in the middle of the highlands of Iceland at a rather high altitude (640-840 m.a.s.l.). The location of the cable is far from populated areas and the current road system is not built to sustain heavy transport. It is probable that the road system, including bridges, needs to be reinforced before the project starts.

The weather can be very harsh in the area, which will, along with accessibility constraints, result in short working seasons. A likely period for work on site is between June and October each year, also depending on the level of road reinforcement. However, even within this short time-frame, difficult weather conditions may constrict the work. The work crew needs to be ready to start work as soon as weather conditions allow. In total, it is expected that the entire work on the project takes around 10 months, which will spread out over 2 years.

From a civil engineering standpoint, the area is expected to be relatively easy for installing a cable.

In this case, it is assumed that there will be one cable set installed in a trench which is excavated with traditional methods. The excavated material will be placed along one side of the trench and the access for the cable installation will be from the other side. Each cable section is expected to be around 1 km in length with around 50 joint bays in total along the route. A standard cross-section can likely be used along the entire route. In general, it is expected that the excavated material can mostly be re-used for backfill and to even out of the surface. The necessary width of the trench will be defined by the space needed for the three conductors and the necessary working space along the conductors in the trench.

No construction or projects are planned nearby the cable route, so the cable is not likely to be disturbed by other future activities. This will define the need for markings and protection in the trench in the section design. Having in mind that there is little risk of other projects/excavations being made in the area in the near future, it could be an option to excavate the trench shallower than normally. The benefit of this would need to be compared to the risk, e.g. issues that could arise such as frost/thaw problems around the cable and danger from erosion in certain places.

The main prerequisites for this case are as follows:

- The length of the route is 50 km.
- One set of cables will be installed.
- Each cable section is expected to be around 1 km, resulting in a total of 50 joint bays.
- A general cross-section for the cable trench is used as a baseline, except in the crossings.
- A service road is needed along 50% of the cable route.
- Total work time is expected to be around 10 months in two summers.
- Average bedrock amount is assumed 5% of the trench section.
- Excavated material is used as backfill.
- Conductors are pulled in pipes in crossings.
- A work camp is needed for two years.
- Reinforcement of the existing road system is needed.

If conflict between the excavation crew and cable laying/jointing crew arises it is possible to excavate the trench and lay out pipes for the conductors, which would then be pulled into the pipes later, thus gaining better utilization of the time spent in the earthwork. This could also reduce conflict between certain tasks of the project and simplify the management, having a better focus on each task.

This alternative with the ducts will, however, not be analysed further here, as it is assumed that the cables can be laid in open trench.

Work Camp

The contractor needs a complete work camp for the crew during the whole work time. This includes, but is not limited to:

- Living areas.
- Canteen building.
- Storage buildings.
- Water and sanitary arrangements.
- Electricity and heating.
- Transportation of people and materials to/from work camp.
- Large storage area.
- A first aid station.
- Communication gear such as GMS and radio.

This also includes extra focus on restoration of the area used for the work camp and clean up at the end of the project.

Safety Measures

Since the area is remote, there is little need for extra safety measures around the site, although standard markings and fences should be used, especially along the mountain road near the working site. During the work there will be a need for extra measures to ensure worker safety, as an emergency response would not arrive quickly in case of an accident.

Excavation and Backfill

No special issues are expected regarding excavation and backfill in this area. Some minor uncertainty may exist regarding the extent of bedrock that needs to be excavated or if permafrost becomes an issue.

Weather conditions may influence the work. If the temperature drops unexpectedly, the installation process could stop. It is expected that the trench cannot be kept open for a long time so the cable laying and excavation teams need to work closely together. The soil in the area can also be sensitive to excess of water and frost/thaw cycles. This can make any work performed in spring difficult without special preparation.

Crossings

There are not many crossings in the area that will cause difficulties. Typical crossings in this area are small creeks, channels, and minor rivers.

Cable Installation

The only real issue with cable installation and handling that is foreseen is the remoteness of the area and unreliable weather conditions which can cause difficulties and/or delays. The working team must be prepared for heating the cable before installation if the temperature drops below -5°C, even though the mean temperature is above 5°C.

Infrastructure and Access Roads at Site

Existing infrastructure in the area, which normally has to be taken into account, is limited. However, the cable route is chosen along an existing fibre optical cable and one main mountain road that leads to the working area from the south. The road splits up in several directions, leading to different areas in the northern part of the country. This main road from the south needs to be rebuilt and maintained for heavy transport of, for example, cable drums.

The soil can be sensitive in wet weather and it is therefore important to maintain the access roads and service roads as conditions allow.

At the same time it must be considered that in some areas the service roads must be hidden in the landscape or removed after the project is done.

Surface Treatment

The surface of the area does not have much vegetation and therefore any treatment will aim at evening out surface and hiding any disturbance made, but not to re-vegetate the disturbed areas. In addition, any roads and work camp areas that will not be allowed to remain should be removed completely.

5.2.6 Cost Estimate

Investment Cost Estimate

The investment cost estimate is made using a cost risk assessment approach, in order to capture the uncertainty in the estimate. Each cost item is evaluated with a three point estimate using the: most likely cost (P), a lower bound of cost at 90% probability of overrun (P_{10}) and an upper bound of cost with 10% probability of overrun (P_{90}). Table 5-6 shows the main cost items after summarising each sub-item. Each sub-item is assumed to have triangular distribution, while the normal distribution describes main cost items reasonably well if they are based on many sub-items.

The following assumptions are made in the cost estimation:

- Cable length = 50 km
- Cable type = 3x1x2000 mm^2 Al segmented conductor
- Distance between joints = 1000 m
- Construction time = 2 years
- Interest rate during construction = 5.5%
- Exchange rate is considered with uncertainty, assuming most likely value, 160 ISK/€, P_{10} = 153 ISK/€ and P_{90} = 167 ISK/€
- Tax on cable material = 0%
- Correlation between cost items = 0.3

Table 5-6. Investment cost estimate for Case I - Sprengisandur.

Cost item	Lower bound, P_{10}	Most likely, P	Upper bound, P_{90}
	[MISK]	[MISK]	[MISK]
Cable - material, joints and joints work	1,873	2,316	2,759
Compensation and end connections	1,040	1,326	1,664
Civil work, earthwork and cable laying	1,384	1,961	2,537
Preparation and permits	161	204	247
Design, supervision and managing	365	470	575
Financial cost	317	371	421

The overall cost estimate is calculated by a Monte Carlo simulation using the @Risk program. The result is shown in a form of probabilistic estimate, presented in figure 5-5. The distribution of the cost needs to be considered for the decision making process but the values used for the project manager (P_{50}) and the steering group (P_{85}) as defined in chapter 4.2 are:

- Project median cost estimate (P_{50}) = 6648 MISK (133,0 MISK/km)
- Project cost estimate, for steering group (P_{85}) = 7543 MISK (150,9 MISK/km)

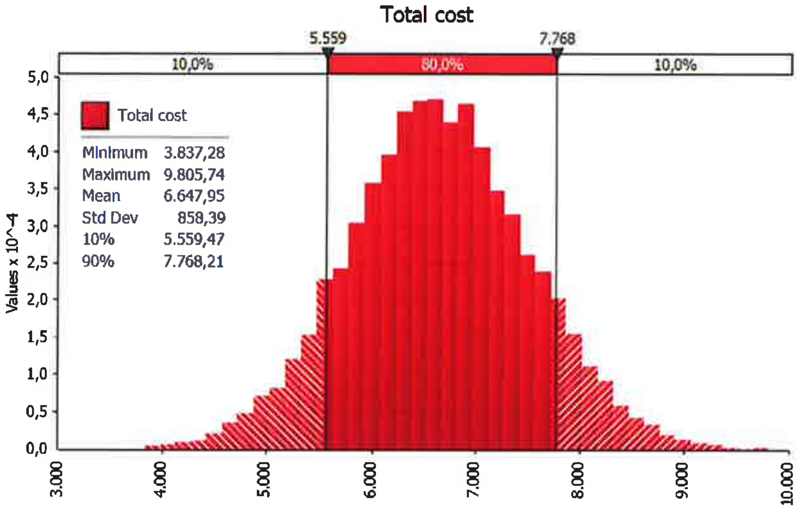

Figure 5-5. Cost estimation, distribution of the overall installation cost using a cost risk approach.

The cost ratio of each main cost item is shown in figure 5-6. The contract with the cable manufacturer is the largest part and covers 35% of the cost. The cable installation is the second largest cost, covering 29% and the compensation and end connections is the third largest cost item covering 20% of the cost.

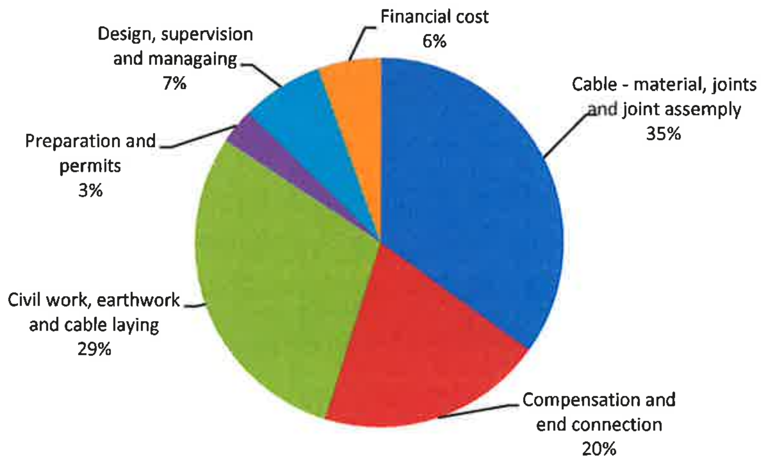

Figure 5-6. Distribution of the cost into main cost items.

Life-Cycle Cost Estimate

A life-cycle cost estimate (LCC) is an estimate of the total cost of ownership and operation from its inception to the end of its useful life to final decommissioning and disposal. Net present value (NPV) is used to bring all expenses of a project to a present day value.

The following assumptions are made in the LCC cost estimate:

- Interest rate = 5.5%
- Yearly cost of operation, maintenance and failure = 0.5% of investment cost.
- End of life cost, dismantling. Estimated as 6% of initial cost.
- Operational life of cable = 40 years.
- Investment cost is assumed to be the P_{50} value.

- Energy losses. Maximum load in the first year of operation = 30% of the cable capacity. Yearly increase is linear until 100% capacity is reached in 40 years. Yearly usage factor = 0.8.
- Cost of losses. Assumed to start at 3.5 ISK/KWh in the year 2014 and rise yearly by 2.5% yearly until it reaches 6 ISK/KWh. It is assumed not to exceed 6 ISK/KWh.

Figure 5-7. Assumptions made for yearly losses and energy price of losses.

The LCC cost is presented in Table 5-7. The investment cost is the most significant cost containing 81.1% of the total LCC cost. Cost of losses is second largest with 11.4% of the total cost.

Table 5-7. Life cycle cost estimate for Case I – Sprengisandur. Values are NPV.

Life cycle cost estimate	Case I	
	[MISK]	[% of total]
Investment cost	6648	86,2%
Losses	450	5,8%
Operation, maintenance and failure cost	563	7,3%
Dismantling	47	0,6%
Total LCC cost	7708	100,0%

5.4 Case II - EYJAFJÖRÐUR

5.4.1 Detailed Description

This case study involves replacing a 12 km part of a 90 km long proposed 220 kV overhead line with an underground cable. The line will lie between the town of Akureyri and Krafla in northern Iceland. The line section in question is the first part (12 km) of the line route, going from the Kífsá substation in Akureyri, as indicated by the dashed line in the simplified diagram in figure 5-8.

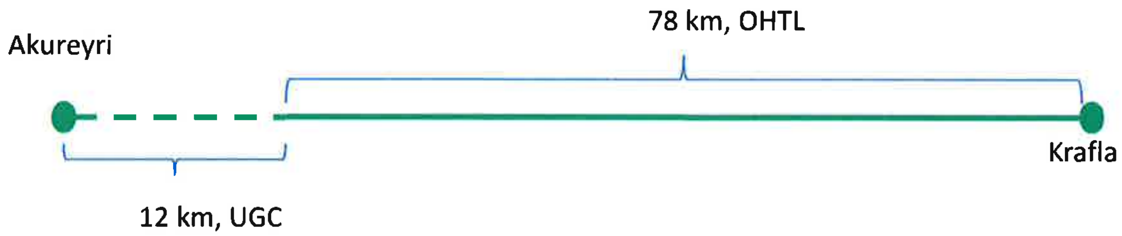

Figure 5-8. A simplified drawing of the proposed Akureyri-Krafla connection.

To be able to reach the same transmission capacity as the proposed overhead line, two sets of cables will have to be installed. This will also be necessary to maintain the required level of security with an adequate transmission capacity. By lowering the requirement for reliable transmission capacity, a single cable set may be applied, relying on the existing 132 kV overhead line as a reserve route. It might be economical to postpone laying the second cable set and rely on the existing 132 kV line.

5.4.2 General Conditions on Cable Route

The proposed cable route extends from the planned connection point near Kífsá, slightly west of Akureyri. From there it follows the present installations towards the recreational area of Kjarnaskógur Forest (hereby referred to as Kjarnaskógur). Three different cable routes were studied from Kjarnaskógur towards the airport (see figure 5-9):

a. North of Kjarnaskógur and underneath Akureyri airport.
b. Alongside existing paths through Kjarnaskógur, then through the southern boundary of the forest and the southern end of the Akureyri airport.
c. Alongside existing paths through Kjarnaskógur and from there it follows existing OHTL a bit further to the south and across Eyjafjarðará river.

All the routes then cross the Eyjafjarðará River and fluvial plains at slightly different locations towards the installations on the east side of the valley.

Several options are proposed for the cable route but in general the geological features are quite similar between the routes. The routes start in 220 m.a.s.l. in Kífsá substation above (west of) Akureyri, and run through grassland and pastures until they reach the slope down to the Eyjafjörður delta. The slope is vegetated with a combination of trees and occasional outcrops of rock. On the east side of the delta the route goes uphill, reaching 130 m.a.s.l., at which point the overhead transmission line starts. The vegetation in the slope on the east bank of Eyjafjörður is mainly agricultural grassland.

The average yearly temperature in Akureyri is 4.1°C for the period from 1994 – 2014. The average for June, July and August is 10.7°C for the same period. The warmest week in that observation period averaged 16.9°C, and daily values can be well above 20°C.

The landscape of the proposed routes can be divided roughly into three different soil categories, 1, 2 and 3 in table 5-8. In the rather gentle sloping area above Akureyri, and in the higher part of the route on the east side of Eyjafjörður, the soil consists of peat with thin layers of ash and organic soil. Drainage ditches have been buried in large sections of this area. Nevertheless, the groundwater level is rather close to or at the surface in most parts of these sections. Bedrock is also at surface level in several areas. In the steeper slopes on both sides of Eyjafjörður, from the level basin and up to tens of meters up the hills, organic soil can be found on the surface with eolian soil underneath. The groundwater level varies in these areas. In addition, occasional rock outcrops and wooded areas are located on the west bank. In the basin of Eyjafjörður is the Eyjafjarðará fluvial plain. On the surface the fluvial plain consists of about 20-30 cm thick organic soil, mainly peat, beneath which are thick sediments of fluvial sand. The groundwater table is almost at surface level. The fluvial plains are highly permeable and dewatering will be a major issue in any trenching across the plains.

The ability of the ground on the route to dissipate heat varies extensively. Peat and organic soils, which cover the largest part of the area, are very poor thermal conductors despite of the high water content. The aeolian sand in the slopes close to the basin has better thermal properties but the presence of organic matter and ash can still increase the resistivity locally. In addition, these areas are the only ones where low moisture content could be an issue. The sand in the delta has reasonable ability to dissipate heat, although that depends on the saturation level.

All the routes have three major crossings, not including the crossing of existing infrastructure such as underground pipes and cables. The first crossing is the Glerá river, which runs through Akureyri. At the proposed location of the crossing the river lies in a small gully. The second main crossing is the Akureyri airfield. One of the proposed routes lies under the runway. The third crossing is the Eyjafjarðará river which runs in several channels on the fluvial plains of Eyjafjörður. All the routes have to cross Eyjafjarðará but the width of the channels varies between locations.

Several borrow areas are in the vicinity of the cable routes. The most promising, as a supply for backfill material, is close to Glerá river near the route. The material in that area consists of fresh basalt.

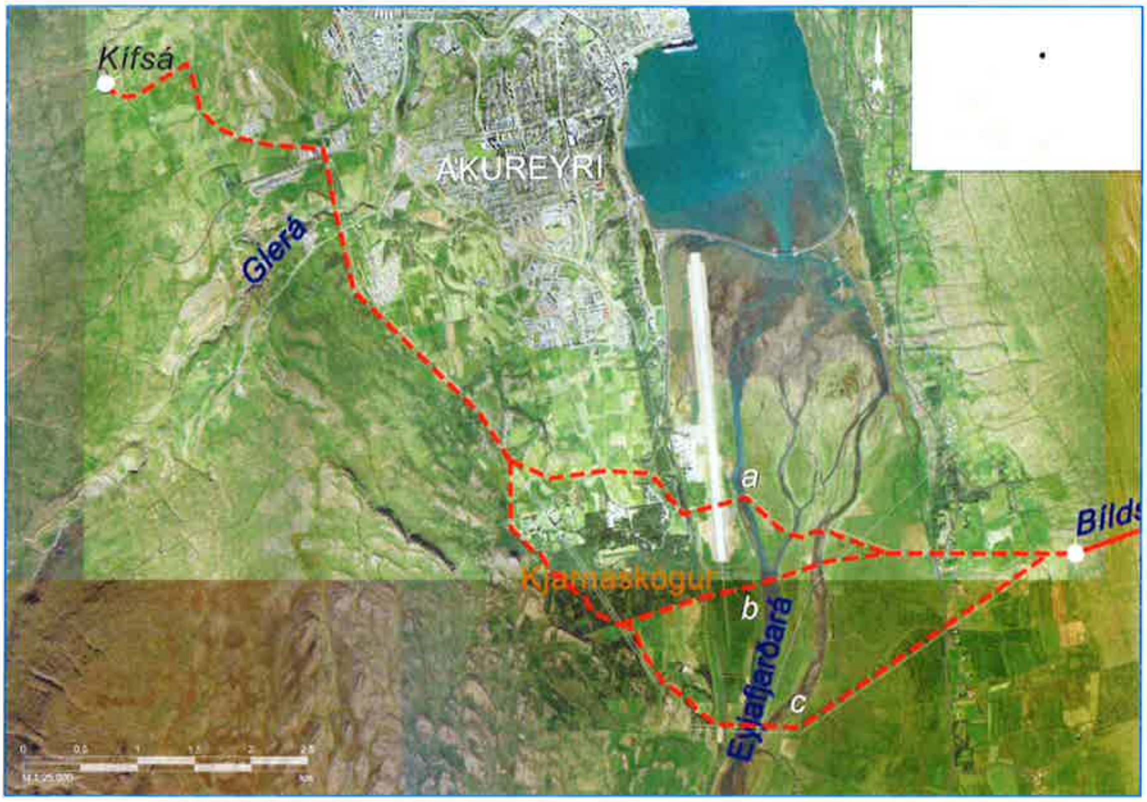

Figure 5-9. Case II – Eyjafjörður. The cable routes that were studied in Eyjafjörður are shown in red dashed lines. The red continuos line at the right side of the map is the end of the transmission line in air. A larger map is in Appendix A.

Table 5-8. General conditions on the cable route in Eyjafjörður.

Section	1		2		3	
	Mean	Max (worst case)	Mean	Max (worst case)	Mean	Max (worst case)
Thermal Resistance: in situ [K*m/W]	1.25	2.00	1.50	2.20	1.80	3.00
Thermal Resistance: backfill material (local) [K*m/W]	1.20		1.20		1.20	
Air Temp (annual mean) [°C]	4.1°C		4.1°C		4.1°C	
Air Temp (summer weekly mean) [°C]	10.7°C	16.9°C	10.7°C	16.9°C	10.7°C	16.9°C
Air Temp typical selected value [°C]	10°C		10°C		10°C	
Conditions	Fluvial sediments		Aeolian soil, partly organic		Peat, highly organic	

5.4.3 Prerequisites

The purpose of this case is to find a viable solution to attain a transmission capacity of 600 MVA through the Eyjafjörður area.

The main prerequisites for the Eyjafjörður case are as follows:

- The cable power transmission capacity shall be 600 MVA, which equals the ampacity value of 1575 A.
- The laying depth is 1.1 m. The trench depth is 1.2 m and the bottom width is 1.0 m. The first 0.1 m are filled with thermal backfill material and the total thermal backfill height is 0.5 m (measured from trench bottom).
- The air- and soil temperature is 10°C.
- The thermal resistance of the surrounding soil is 1.5 K*m/W (mean value).
- The basic backfill material has a thermal resistance of 1.2 K*m/W.
- The laying formation is flat formation, with (120+D) mm between cable centers. Two parallel sets of cables will be laid, with approximately 10 m between trench centers. This distance allows the mutual thermal influence to be neglected.
- Screens are cross bonded.
- Allowed continuous temperature on the cable outer sheath is 50°C. This corresponds to a calculated conductor temperature of approximately 65°C.

5.4.4 Calculations and Limits

Current Rating

In the following section, two variants of cable cross sections and designs are compared. The calculations are the results of numerical analysis, where a typical cable with stranded Al conductors is modelled, along with the thermal backfill, excavated/competent backfill, and surrounding native soil. The results are shown in table 5-9 below.

The base variant for Eyjafjörður was defined as two parallel sets of 3x1x1600 mm^2 Al cables with stranded conductors.

As shown in the table, a variant with copper conductors was compared for cost optimization. The required current carrying capacity cannot be fully achieved with the thermal backfill available at site, but could be reached by adopting higher quality materials at extra cost.

Table 5-9. Comparison of two variants of cable cross sections and designs.

Variant	Cable Type	Backfill th. Res. K*m/W	Backfill height mm	Conductor Temp °C	Current rating A	MVA %
Base variant	2x 3x1x1600q Al	1.2	500	65	1844	117%
Variant 2	3x1x2500q Cu	1.2	500	65	1491	95%

Reactive Compensating Units

The general assumptions, based on load flow calculations, are that special compensation is not needed in this case. However, care must be taken (and more detailed analyses to be performed) on the case with a double set of cables with the “eastern end” open, as the voltage at the Akureyri-end could become unacceptably high. Figure 5-10 is a simple illustration of this case.

Figure 5-10. Illustration of the case when the overhead section opens.

The tripping of the overhead section of the line will lead to a voltage step at Akureyri 220 kV bus, as illustrated in figure 5-11 below. In the same figure, the response with a 30 Mvar shunt reactor at Akureyri is shown for comparison.

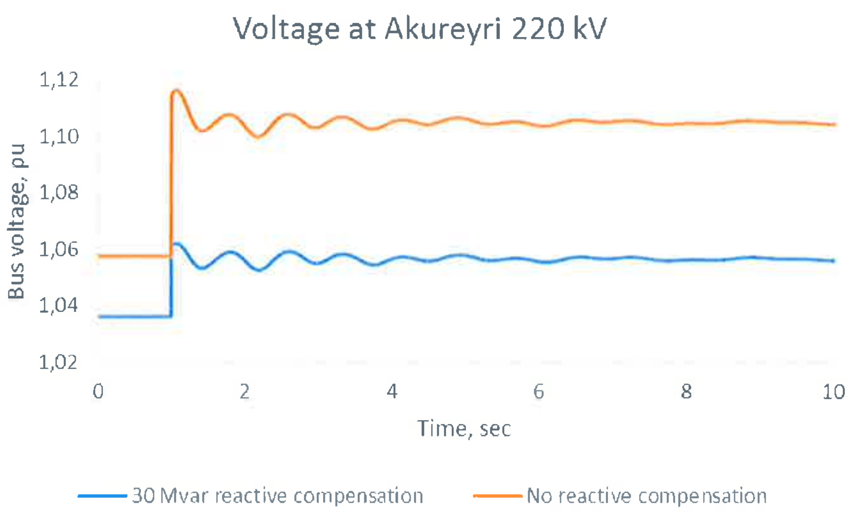

Figure 5-11. Voltage step at 220 kV Akureyri when the overhead section of the link opens.

As figure 5-11 shows, it is possible to reduce the voltage step greatly by compensating. The simulated voltage step is on the edge of what is accepted by quality requirements (5%) and the post-fault value of voltage is above 1.1 pu, so one may conclude that this case of a double set of underground cables, i.e. 2x12 km, is on the margin of what is possible without compensation. The no-load reactive power production of such a double set of cables is approximately 73 Mvar (referred to a voltage of 1.0 pu).

It is assumed that when the line is subject to a trip like this, the whole line would be tripped. Thus, no voltage rise would be experienced.

At present there is a 3x20 Mvar capacitor bank connected to the 132 kV bus at Rangárvellir substation. It is to be expected that a set of underground cables, as described here, would reduce the need for this bank significantly.

5.4.5 Cable Installation

General

The area provides interesting challenges for civil works when considering underground cable installation. To provide a cost benefit the route needs to be kept as short as possible and factoring in various difficult crossings and conflicts with local infrastructure. The route also has varying soil conditions and in general demanding surface treatment. The closeness to populated areas means that the project facilities such as work camps are easier to manage and material will be more accessible. But this will also call for more markings/measures in the trench to protect it in case of future construction projects.

The route will also travel along mountain slopes on each side and it is expected that sections with hard materials will have to be excavated. Furthermore, since some of the excavated material is expected to be peat and organic material, there will be a need to replace some of these with competent materials.

The base analysis assumes that the trench will be excavated using a normal cross-section for the cable trench and directional drilling under the rivers and the airfield will be used. Other possibilities are also considered in comparison where possible. The standard trench size will be used here for comparison purposes.

It is likely that water will be a major cause for difficulties in excavating some parts of the route. An excavation box could be used on a part of the route instead of excavating the trench by traditional methods. This would mean a smaller opening at a time, which would possibly be easier to keep dry, but then the cable would have to be installed simultaneously.

Freezing the soil while excavating could be considered, in order to reduce the influx of water. This will likely prove very costly and should only be used if other methods are ineffective.

It should be considered to install pipes in the river area beforehand to minimize the time that the excavation needs to remain open.

Perhaps it will furthermore be necessary to create a watertight box around the joints (for example concrete boxes) to ensure the working conditions within the site.

The main prerequisites for the three cases are as follows:

- The lengths of the three routes are similar, about 12-13 km long.
- Two sets of cables will be laid, in separate trenches.
- Both cables are assumed to be installed simultaneously.
- Each cable section is expected to be around 1 km, therefore a total of 24 joint bays is needed for both sets.
- General cross-section for the cable trench is used as a baseline, except the directional drilling parts under the airfield and the rivers.
- A service road is needed for up to 80% of the cable route.
- Total work time is expected to be around 8 months in the period of March-October.
- Average bedrock amount is assumed to be 15% of the trench section.

Work Camp

The project site is within the town of Akureyri, so the need for a work camp will be minimal, comprising of facilities for coffee breaks and work meetings but without sleeping/dining areas. A base for operation and a storage area for equipment, drums and other material for the project will also be needed.

Excavation and Backfilling

Since the route reaches from one mountain slope, across a river valley to another mountain slope, the soil conditions vary along the route. Most of the route along the river valley is expected to be soft soil, which will be easy to excavate, except in the areas near the river where the water table is high and the soil saturated. Some of that material is probably not suitable for backfill and will be replaced by better materials. Bedrock needs to be cleared from the trench in the mountain slopes and removed.

In some places, especially around the river area, it will most likely be possible to use an excavation box to install the cables properly. This is due to high water levels and the softness/lack of stability of the soil.

It is very likely that at least one joint bay will be in a difficult part of the river area, calling for special solutions such as a gravel bottom with proper pumping to ensure the work area.

Although the fill work in general is expected to be straightforward, it will be difficult along the river area. For most of the area suitable soil material should be easily found close by, but will need to be transported to the trench.

Safety Measures

Since the area is close to a populated area, safety measures are very important. This includes markings, warnings, and possibly the installation of fences around the work area to ensure the safety of bypassing traffic and workers.

Crossings

The number and difficulty of the crossings is a major issue in this case for all three alternatives. The biggest difficulties will lie in crossing the rivers of Eyjafjarðará and Glerá. A lot of infrastructure utilities and cables already exist within the area which need to be considered and crossed. These include power cables, hot and cold water pipes, and various communication cables. This applies especially to the area around the Akureyri airport, which the cable route either crosses or lies close by. Because of this, directional drilling is expected to be used, even though it is expensive. However, the distance that can be reached this way is limited. At present, the available equipment in Iceland can only reach up to 500m in good drilling conditions.

Two major roads will have to be crossed. This can be done by normal drilling under the road and leaving pipes which the cable is then pulled into. Drilling under the road might be more viable than excavation, as it doesn't disturb the road traffic and eliminates the need of installing a temporary bypass.

Finally, there are many small trenches, small roads and fences that have to be crossed but these can likely be crossed using normal excavation methods.

It has been discussed during the planning to use directional drilling underneath the wooded areas. However, this has been previously attempted in Iceland with mixed results (Nesjavallalína 2). It is therefore recommended that a cable route through forested areas follows existing paths to the extent possible to minimise damage.

Cable Installation

Due to many crossings and turns along the route, the installation process must be planned and executed in detail. In this project, traditional excavation (chapter 3.3.2) is expected to be used, except in the wet area near Eyjafjarðará river where the use of excavation box is planned (chapter 3.3.4).

Infrastructure and Access Roads

Since the cable route is within a populated area there will be many structures and utilities that the design will need to take into consideration so that the project can be successfully completed.

There are several access roads and smaller dirt roads in the area that can be used as service roads, especially if the route design takes their presence into consideration. However, additional service roads will be needed, some of which will be removed after the work is done, while other roads will be allowed to remain as dirt roads or footpaths. The main service road will be located between the two cable sets.

Surface Treatment

Since most of the area is vegetated the surface treatment after construction will in most cases involve the restoration the vegetation to its previous state. Preserved topsoil will be reused where possible and grassland will be restored by seeding and/or fertilisation.

In forested areas, it is expected that some of the service roads will be allowed to remain for later use as footpaths.

5.4.6 Cost Estimate

Investment Cost Estimate

The investment cost estimate is made using the same approach as described in chapter 4.2 and chapter 5.2.6 Investment Cost Estimate. Four different alternatives were estimated, i.e. the three different routes and an additional alternative for the Kjarnaskógur route using 4 copper cables. The spare cable is to reduce time of unavailability in case of failure. The alternatives are described in table 5-10.

Table 5-10. Alternatives for case II - Eyjafjörður

Case	Description	Cables	Capacity [MVA]	Length [km]	Distance between connections [m]
II-a	Route under airport, two sets of cables.	6x1x1600q Al	700	11.69	1,000
II-b	Through Kjarnaskógur, two sets of cables.	6x1x1600q Al	700	12.37	1,000
II-c	Following proposed OHTL route, two sets of cables.	6x1x1600q Al	700	13.21	1,000
II-d	Through Kjarnaskógur, 4 copper cables.	4x1x2500q Cu	570	12.37	1,000
II-e	Through Kjarnaskógur, one set of cables.	3x1x1600q Al	350	12.37	1,000

The following assumptions are made in the cost estimation:

- Construction time = 1 year
- Interest rate during construction = 5.5%
- Exchange rate is considered with uncertainty, assuming the most likely value = 160 ISK/€ (P_{10} = 153 ISK/€ , P_{90} = 167 ISK/€)
- Tax on cable material = 0%
- Correlation between cost items = 0.3

Table 5-11 shows the P_{50} value of the main cost items and the resulting P_{50} and P_{85} cost value for the total cost. Alternative II-b has the lowest cost. Alternative II-a is 7.3% higher and the cost difference is due to the higher cost of civil work, since it includes difficult crossings. Alternative II-c is 3.4 % higher than II-b, mainly due to longer cable length. Alternative II-d is expensive and it is evident that the copper cable alternative is not competitive in terms of cost.

Table 5-11. Investment cost estimate for different alternatives in Case II - Eyjafjörður. Cost items are given as the most likely cost.

Cost item	Case II-a			Case II-b			Case II-c		
	Under airport			Through Kjarnaskógur			Following existing OHTL		
	[MISK]	[MISK/km]	[%]	[MISK]	[MISK/km]	[%]	[MISK]	[MISK/km]	[%]
Cable - material, joints and joints work	979	83.8	34.9	1036	83.8	39.6	1106	83.7	40.9
Compensation and end connection	61	5.2	2.2	61	4.9	2.3	61	4.6	2.2
Civil work, Earthwork and cable laying	1,301	111.3	46.3	1,056	85.3	40.3	1,059	80.1	39.1
Preparation and permits	140	11.9	5.0	138	11.2	5.3	147	11.1	5.4
Design, supervision and managing	226	19.3	8.1	229	18.5	8.8	233	17.6	8.6
Financial cost	103	8.8	3.7	98	7.9	3.7	102	7.7	3.8
Median cost estimate (P_{50})	2,809	240.3		2,618	211.6		2,706	204.9	
For steering group (P_{85})	3,373			3,061			3,137		

Table 5-12. Investment cost estimate for alternatives "d" and "e" in Case II - Eyjafjörður. Cost items are given as the most likely cost.

Cost item	Case II-d			Case II-e		
	Copper cables			Through Kjarnaskógur		
	[MISK]	[MISK/km]	[%]	[MISK]	[MISK/km]	[%]
Cable - material, joints and joints work	2260	182.7	40.9	529	42.8	38.4
Compensation and end connection	60	4.9	2.2	36	2.9	2.6
Civil work, Earthwork and cable laying	750	60.6	39.1	559	45.2	40.6
Preparation and permits	140	11.3	5.4	89	7.2	6.5
Design, supervision and managing	200	16.2	8.6	113	9.1	8.2
Financial cost	150	12.1	3.8	51	4.2	3.7
Median cost estimate (P_{50})	3,560	287.8		1,378	111.4	
For steering group (P_{85})				1,612		

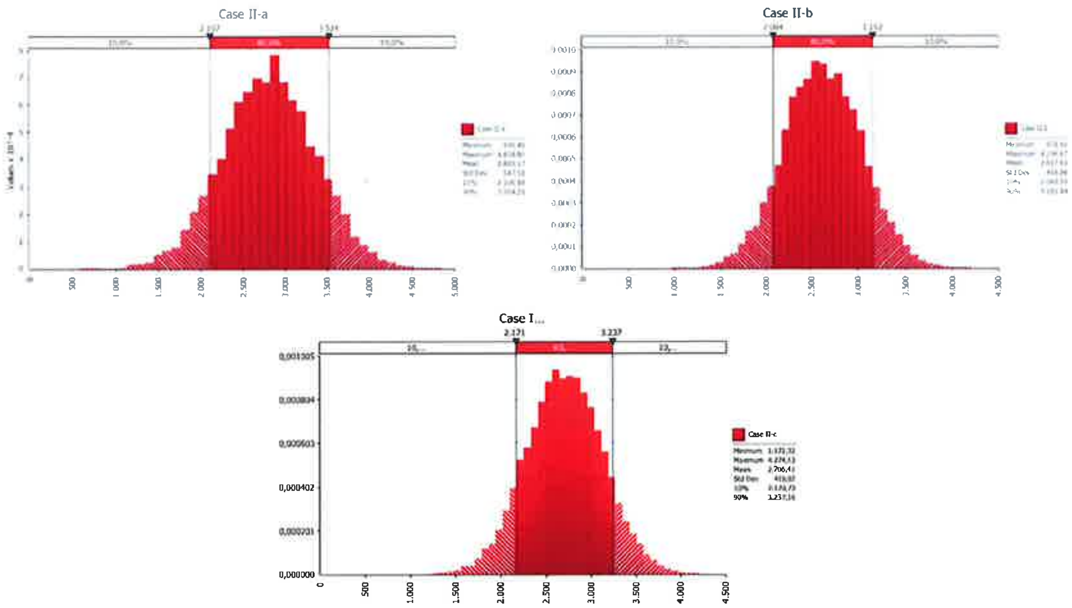

Figure 5-12. Cost estimation, distribution of the overall installation cost using a cost risk approach.

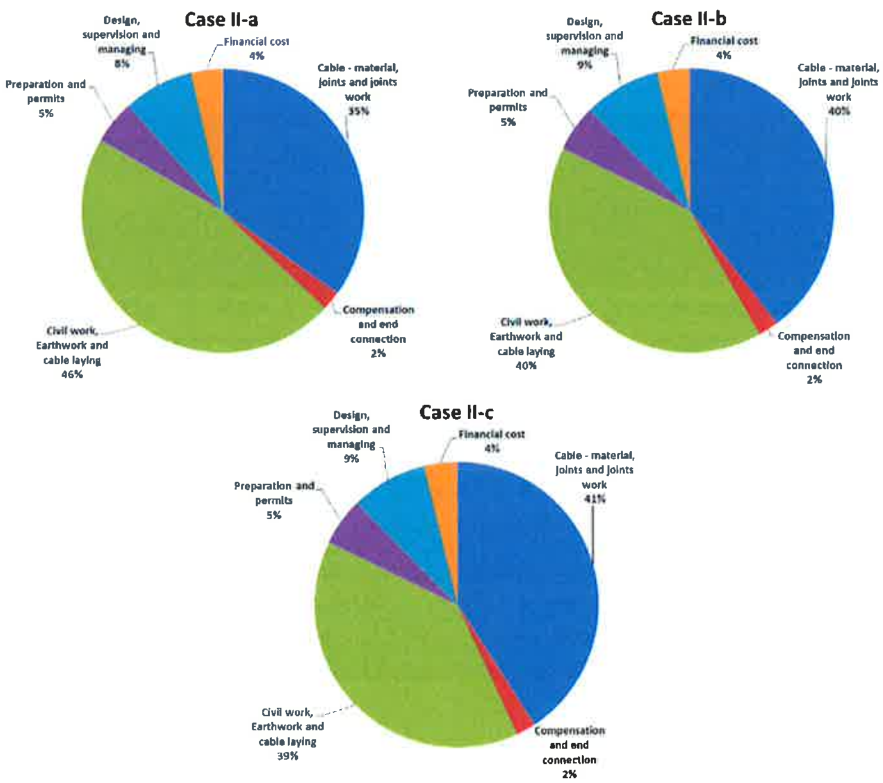

Figure 5-13. Distribution of the cost into main cost items.

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Life-cycle cost estimate

The following assumptions are made in the LCC cost estimate:

- Interest rate = 5.5%
- Yearly cost of operation, maintenance and failure = 0.5% of initial cost.
- End of life cost, dismantling = 6% of initial cost.
- Operational life of cable = 40 years.
- Investment cost is assumed as the P_{50} value.
- Energy losses. Maximum load in the first year of operation = 60% of the cable capacity. Yearly increase is linear until 100% capacity is reached in 40 years. Yearly usage factor = 0.8.
- Cost of losses. Assumed to start at 3.5 ISK/KWh in the year 2014 and rise yearly by 2.5% until it reaches 6 ISK/KWh. It is assumed to do not exceed 6 ISK/KWh.

The Life Cycle Cost (LCC) cost is presented in Table 5-13. The investment cost is the most significant cost containing around 85 % of the total LCC cost. Cost of losses is similar to the cost of operation, maintenance and failure. Alternative II-b has the lowest LCC cost.

Table 5-13. Life cycle cost estimate for Case II – Eyjafjörður. Values are NPV.

Life cycle cost estimate	Case II-a		Case II-b		Case II-c	
	[MKr]	[% of total]	[MKr]	[% of total]	[MKr]	[% of total]
Investment cost	2,809	84.7%	2,618	84.3%	2,706	84.5%
Losses	248	7.5%	248	8.0%	248	7.7%
Operation, maintenance and failure cost	238	7.2%	222	7.1%	229	7.2%
Dismantling	20	0.6%	18	0.6%	19	0.6%
Total LCC cost	3,315	100%	3,106	100%	3,202	100%

5.6 Case III – HAFNARFJÖRÐUR

5.6.1 Detailed description

This case study involves the partial undergrounding of Suðurnesjalína 2. The line is 32 km long and will connect Hamranes and Rauðimelur substations. The line section in question is the first part (1.5 km) from Hamranes substation in Hafnarfjörður, as indicated by the dashed line in the simplified diagram in figure 5-14.

As pointed out in the prerequisites below (chapter 5.6.3), laying a single cable set is analysed. Another cable set may be installed at a later stage, depending on development of load and production in the region. As indicated in figure 5-14 there is another transmission line connecting Hamranes and Fitjar substations (at 132 kV voltage), thus the required level of reliability is preserved, even with just one cable set.

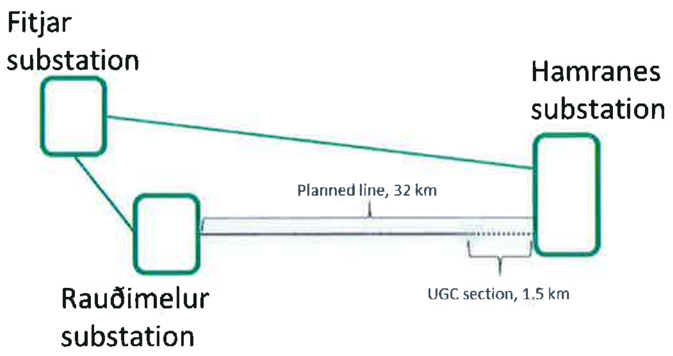

Figure 5-14. A simplified drawing of the proposed line between Hamranes and Rauðimelur substations.

5.6.2 General conditions on cable route

The proposed underground cable route runs nearly 1.5 km from the Hamranes substation towards the Rauðamelur substation. The area is just south of the residential area of Hafnarfjörður and passes through a planned industrial area. The route is at an elevation level of approximately 30 m.a.s.l. and is entirely within a rather young lava formation. Site investigations for overhead transmission lines have been carried out in the area. In addition, groundwater and water supply studies have been performed. The area is in an active rift zone with high earthquake risk. Still, the risk of direct faulting on the route is assumed to be rather low in this area. There is also a risk of volcanic activities in this area.

The average annual temperature at Straumsvík, which is located just NW off the route, is 5.6°C for the period 1993 – 2013. The average for June, July and August is 10.5°C for the same period. Daily values of above 20°C can occur.

A large part of the route is through lava which has already been disturbed. Vegetation is scarce in the remaining undisturbed areas and the soil layer is thin. The surface layer of the lava called scoria is rough rubble and piles of vesicular stones and slag like fragments of lava. The scoria can be 2 – 4 m thick. Below the scoria is a more solid core of the lava unit. Permeability in lava fields is generally high, and they are normally absent of runoff water. The groundwater table is at approximately 10 m depth.

Due to the high permeability and low groundwater, dry conditions in the cable trench are expected. Water retention is also expected to be poor. As for the thermal dissipation, lava in general has poor properties, and this particular area offers no exception. The scoria is relatively thick, very broken, vesicular, and porous, and is therefore classified a "thermally" poor environment.

There are two well-known and operational borrow areas that come into consideration for this project. Both provide material with reasonable thermal properties by Icelandic standards.

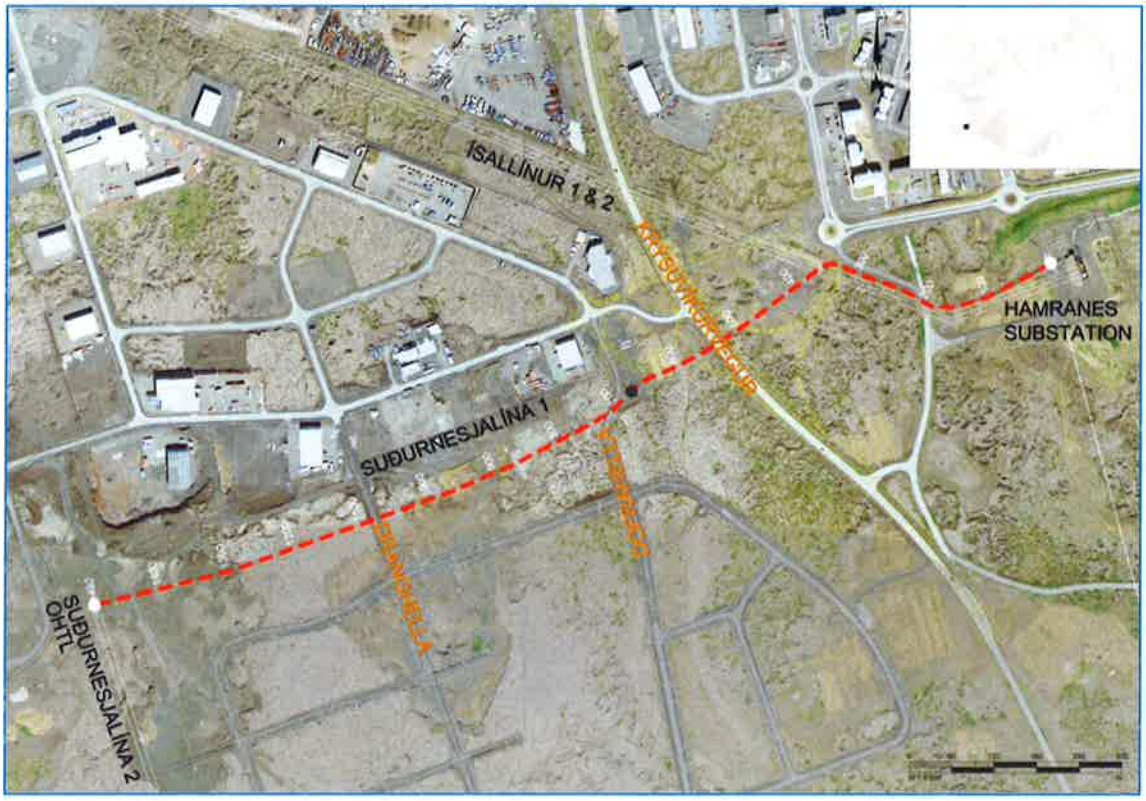

Figure 5-15. Case III – Hafnarfjörður. The cable route is shown in a red dashed line. Yellow dashed lines show the planned road structures. A larger map is in Appendix A.

Table 5-14. General conditions on the cable route in Hamranes.

	Mean	Max (worst case)
Thermal Resistance: in situ [K*m/W]	2.00	3.00
Thermal Resistance: sand (Local) [K*m/W]	1.30	
Thermal Resistance: quartz (Grundartangi) [K*m/W]	0.6	
Air Temp (annual mean) [°C]	5.4°C	
Air Temp (summer weekly mean) [°C]	10.5°C	14.7°C
Air Temp typical selected value [°C]	10°C	
Conditions	Lavafield, pillow lava embankments	

5.6.3 Prerequisites

The purpose of this case is to find a viable solution to attain a transmission capacity of 300 MVA for a 1.5 km cable section near Hamranes substation.

The main prerequisites for the Hamranes case are as follows:

- The cable power transmission capacity shall be 300 MVA, which equals the current ampacity of 788 A. A second cable set with same transmission capacity will be installed at a later stage, depending on development of load and production in the region.

- The laying depth is 1.1 m. The trench depth is 1.2 m and the bottom width is 1.0 m. The first 0.1 m are filled with thermal backfill material and the total thermal backfill height is 0.7 m (measured from trench bottom).
- The air- and soil temperature is 10°C.
- The thermal resistance of the surrounding soil is 2.0 K*m/W (mean value).
- The basic backfill material has a thermal resistance of 1.3 K*m/W, but a special material with 0.6 K*m/W can be applied as an alternative.
- The laying formation is flat formation, with (120+D) mm between cable centers.
- Screens are single point bonded at the center joints and both ends are furnished with SVLs.
- Allowed continuous temperature on the cable outer sheath is 50°C. This corresponds to a calculated conductor temperature of approximately 65°C.

5.6.4 Calculations and Limits

Current Rating

In the following section, a few variants of cable cross sections and designs are compared. The calculations are the results of numerical analysis, where a typical cable with stranded Al conductors is modelled, along with the thermal backfill, excavated/competent backfill, and surrounding native soil. The results are shown in table 5-15 below.

The base variant for Hamranes was defined with 3x1x1600 mm^2 Al cables with stranded conductors.

As shown in table 5-15, a number of alternative configurations can be compared for cost optimization. To achieve an equal current carrying capacity, the cable cross section can be reduced if the quality of the backfill material is improved, either by increasing the amount or by selecting a (more costly) material with better thermal qualities.

Table 5-15. Comparison of a few variants of cable cross sections and designs.

Case	Cable Type	Backfill th. Res. K*m/W	Backfill height mm	Conductor Temp °C	Current rating A	MVA %
Base Case	3x1x1600q Al	1.3	700	65	791	100%
2	3x1x1600q Al	1.3	500	65	762	97%
3	3x1x1600q Al	0.6	500	65	833	106%
4	3x1x1400q Al	0.6	500	65	792	101%
5	3x1x1200q Al	0.6	700	65	804	102%

Reactive compensating units

Due to the short cable length, no reactive compensation will be required.

5.6.5 Cable installation

General

The project consists of one set of cables, which will be laid in pipes for a significant part of the route.

Figure 5-16. Conditions on the cable route at Hamranes.

The selected route partly follows a predefined zone for electrical installations, reaching from the substation at Hamranes to the end of a proposed OHTL, Suðurnesjalína 2. Most of the cable route is already disrupted, but a part of the route is within untouched lava. An emphasis was put on avoiding untouched areas during the route selection. A major road crossing is planned on the route (see figure 5-15). The cable will have to be buried at around 4 m depth in this section, under a landfill. The increased cover will reduce the thermal dissipation of the cable significantly. Extra mechanical protection is recommended for this section.

The work is expected to take about 2 months in total. A joint bay located in the middle of the route has been included in the analysis, but due to existing OHTL this jointing is unfavourable. Thus the possibility of using one section for the entire route is relevant if the cable manufacturers can deliver 1.5 km in one cable drum. The main disadvantage of using such a long section is the many pipes to be pulled through. This option should be considered further since it will most likely save cost in jointing and material.

The project site is within an industrial area additional safety measures are needed during the project's construction and the design should also include extra protection for the cable, such as concrete tiles.

The main prerequisites for this case are as follows:

- The length of the route is 1.5 km.
- One set of cables will be installed.
- One joint bay is expected in the middle of the route.
- A general section is used as a baseline with different solution for crossings.
- A service road is needed along 90% of the cable route.
- Total work time is expected to be around 2-3 months in the summer.
- Average bedrock amount is assumed 50% of the trench section.
- Excavated material is not used as backfill, but a part of it is suitable for the service road.
- Cables are pulled in pipes in crossings and future road crossings.
- Extra protection is needed for the cable and a geotextile has to be installed around the thermal backfill.

Work Camp

This project is located inside the town of Hafnarfjörður, so the need for a work camp will be minimal, limited to facilities for coffee breaks and regular work meetings. Sleeping/dining facilities are not needed. A base for operation and a storage area for equipment, drums and other material for the project will be needed.

Excavation and backfilling

There is extensive lava bedrock in the area. The excavated material cannot be used as backfill and must be removed. Although the working area is small and constrained, a big part of it has already been disrupted and is not sensitive for working traffic. It is considered possible to excavate the surface soil and the scoria part of the lava using conventional excavators. The remaining part of the lava will have to be excavated using hydraulic chiselling, although some lava fields may be fit for ripping with heavy excavators (>45 ton).

Borrow areas providing suitable backfill material are located reasonably close to the site.

Safety measures

Since the area is close to a populated area, and it crosses an important road to a gravel mine, safety measures such as markings and fences around important areas have to be made to ensure the safety of those who pass through the site and the workers. Also, more extensive markings and safety measures will be needed in the trench to protect against later disturbances.

Crossings

Crossings are made by installing pipes. These crossings are at main pipes, electrical- and fiber optical cables, existing roads and future roads.

Access roads at site

The cable route lies through lava with good bearing capacity, so there will probably not be a need for the construction of extensive service roads. In the beginning of work, the surface along the cable route through the untouched lava must be made smooth enough for the excavators to work on and wide enough for the trench and the track.

Surface treatment

The surface treatment will mostly consist of smoothing out to the surrounding landscape after the fill is completed.

The initially preserved surface material will be spread out over the disrupted area. This should speed the restoration of the moss that characterizes the area and help to reconstruct the appearance of the surface.

5.6.6 Cost Estimate

Investment Cost Estimate

The investment cost estimate is made using the same approach as described in chapter 4.2 and chapter 5.2.6. Two different alternatives were estimated, described in table 5-16. The difference between the alternatives is the use of different backfill material. In case III-b quartz backfill material transported to site from Hvalfjörður is used (see discussion in chapter 3.11.2).

Table 5-16. Alternatives for case III - Hafnarfjörður.

Case	Description	Cables	Length [km]	Distance between connections [m]
III-a	Normal backfill material; 1,3 K*m/ W	3x1x1600q Al	1.5	750
III-b	Special backfill material; 0,6 K*m/ W	3x1x1200q Al	1.5	750

The following assumptions are made in the cost estimation:

- Construction time = 3 months.
- Interest rate during construction = 5.5%
- Exchange rate is considered with uncertainty, assuming most likely value = 160 ISK/€, P10 = 153 ISK/€ and P_{90} = 167 ISK/€.
- Tax on cable material = 0%

- Correlation between cost items = 0.3.

Table 5-17 shows the P_{50} value of the main cost items and resulting P_{50} and P_{85} cost value for the total cost. Alternative III-b has 4.1% lower cost than alternative III-a. The benefit of a smaller cable is higher than the additional cost of the special backfill material.

Table 5-17. Investment cost estimate for Case III - Hafnarfjörður.

Cost item	Case III - a			Case III - b		
	Lower bound P_{10}	Most likely, P	Upper bound, P_{90}	Lower bound, P_{10}	Most likely, P	Upper bound, P_{90}
	[MISK]	[MISK]	[MISK	[MISK]	[MISK]	[MISK]
Cable - material, joints and joints work	71	88	104	61	75	89
Compensation and terminations	5	12	19	5	12	19
Civil work. Earthwork and cable laying	64	92	119	67	95	124
Preparation and permits	7	10	13	7	10	13
Design, supervision and managing	21	27	33	21	27	33
Financial cost	5	6	8	4	6	6
Median cost estimate (P_{50})	235			225		
For steering group (P_{85})	271			260		

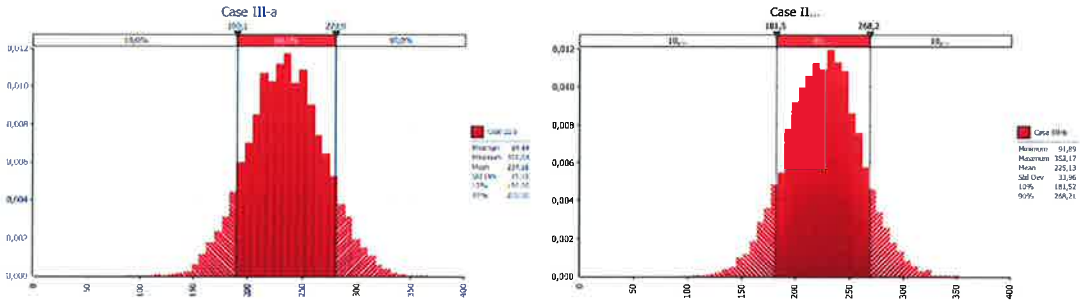

Figure 5-17. Cost estimation, distribution of the overall installation cost using a cost risk approach.

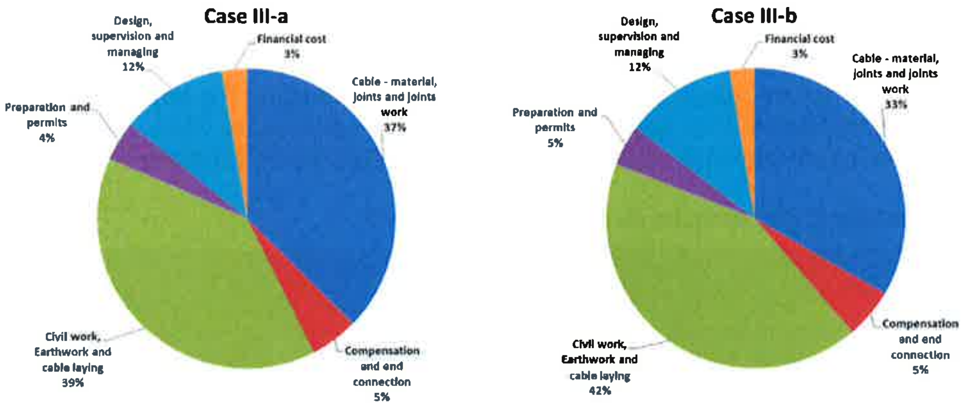

Figure 5-18. Distribution of the cost into main cost items.

Life-cycle cost estimate

The following assumptions are made in the life-cycle cost estimate (LCC):

- Interest rate = 5.5%
- Yearly cost of operation, maintenance and failure = 0.5% of initial cost.
- End of life cost, dismantling = 6% of initial cost.
- Operational life of cable = 40 years.
- Investment cost is assumed as the P_{50} value.
- Energy losses. Maximum load in the first year of operation = 60% of the cable capacity. Yearly increase is linear until 100% capacity is reached in 40 years. Yearly usage factor = 0.8.
- Cost of losses. Assumed to start at 3.5 ISK/KWh in the year 2014 and rise yearly by 2.5% yearly until it reaches 6 ISK/KWh. It is assumed to do not exceed 6 ISK/KWh.

The LCC cost is presented in Table 5-19. The investment cost is the most significant cost containing 86% of the total LCC cost.

Table 5-18. Life cycle cost estimate for Case III – Hamranes. Values are NPV.

Life cycle cost estimate	Case III-a		Case III-b	
	[MISK]	[% of total]	[MISK]	[% of total]
Investment cost	235	86.4%	225	84.5%
Losses	15	5.7%	21	7.7%
Operation, maintenance and failure cost	20	7.3%	19	7.2%
Dismantling	2	0.6%	2	0.6%
Total LCC cost	272	100.0%	266	100.0%

5.7 Comparison of cases

5.7.1 Technical aspects

Sprengisandur

Technologically challenging with respect to reactive power compensation and system operation. Due to the difference in system strength between north and south, the need for reactive compensation is variable, based on the operating conditions (e.g. energisation, low load, high load).

The installation process is technically simple. The soil conditions are good, few crossings of roads, rivers, other installations etc. Borrow areas are in near vicinity.

The geographical conditions are challenging. The area is located in the mid of the Icelandic highlands, far away from inhabited areas. Thus transport of cable drums is quite a long distance. Due to the short summer in the highly elevated area, the effective project time would be quite short. The weather may get quite harsh, even in the summer. Thus, the project planning may be challenging.

Eyjafjörður

Not especially technically challenging. The need for reactive compensation is not extensive.

The installation process, however, is technically challenging. The route is in a relatively densely populated area and crosses two major rivers, woodland, airport, and national conservation wet-land. Fairly expensive operations are needed in some crossings and in the wet-land. Borrow areas are located at a medium distance.

The geographical conditions are good. The area is densely populated and the weather conditions are generally good.

Hafnarfjörður

Not especially technically challenging. No need for reactive compensation.

The installation process is somewhat technically challenging due to a few issues: The cable route runs through lava, which can involve hammering; there is a considerable amount of crossings; and major road crossings will be laid over the cable. Furthermore there is need for extra cover of the cable and earth wire throughout the cable route and borrow areas are located at a medium distance.

The geographical conditions are good. The area is populated and the weather conditions are generally good. The distance to borrow areas with quarts sand (with low thermal resistance) is moderate.

5.7.2 Cost comparison

In this chapter the cost of all cases studied in this recearch project are compared. Table 5-19 and the graphical representention in figure 5-19 shows the total unit cost for each case. Differences in conditions at each site, and in cable diameter, are reflected in the price difference. In case III the short length (1.5 km) of the cable gives a fairly high unit price.

Table 5-19. Total unit price for 220 kV cable for the six main cases.

Cost item	Case I	Case II			Case III	
	Sprengisandur	Eyjafjörður			Hafnarfjörður	
		a	b	c	a	b
	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]
Cable – material, joints and joint work	46.3	83.8	83.8	83.7	58.4	49.9
Compensation and end connections	26.5	5.2	4.9	4.6	8.1	8.1
Civil work, earthwork and cable laying	39.2	111.3	85.3	80.1	61.0	63.6
Preparation and permits	4.1	11.9	11.2	11.1	6.7	6.7
Design, supervision and managing	9.4	19.3	18.5	17.6	22.1	19.7
Financial cost	7.4	8.8	7.9	7.7	5.7	5.7
Total (P50)	**133.0**	**240.3**	**221.6**	**204.9**	**161.9**	**153.7**
Steering group (P85)	150.9	288.5	247.5	237.5	188.7	183.3

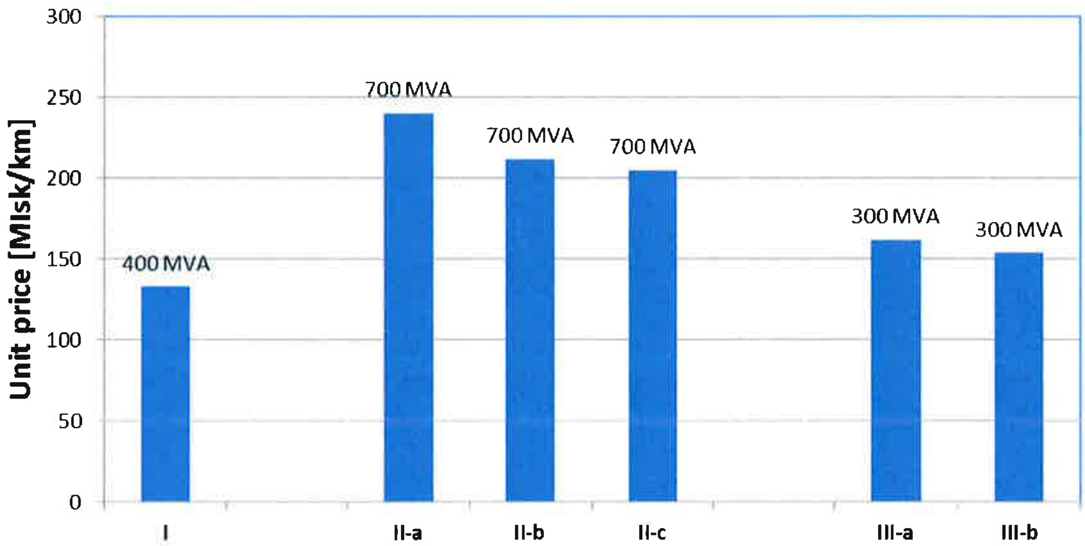

Figure 5-19. Total unit price for 220 kV cable for the six main cases

Figure 5-19 shows the unit price for earthwork for each case. Comparison of the earth work shows very different cost between the cases, reflecting different characteristics of each project.

Table 5-20. Unit price for earthwork for the six main cases.

Cost item	Case I	Case II			Case III	
	Sprengisandur	Eyjafjörður			Hafnarfjörður	
	50 km	11.7 km	12.4 km	13.2 km	1.5 km	1.5 km
		a	b	c	a	b
	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]	[MISK/km]
Work camp and facilities	5.9	6.0	5.7	5.3	4.7	4.7
Civil and earthwork	16.4	29.1	29.8	29.8	36.1	38.7
Cable laying	12.2	19.6	18.9	18.6	14.4	14.4
Crossing	0.2	53.4	28.0	23.7	4.0	4.0
Assist	0.0	0.1	0.1	0.1	0.3	0.3
Other related work	4.5	3.0	2.8	2.7	1.6	1.6
Total	39.2	111.3	85.3	80.1	61.0	63.6

The difference between the unit cost [cost/km] for the three studied cases shows that no national values can be given for all terrain- and grid conditions. On the contrary, the results indicate that the variation between cases is so large that individual studies must be conducted for each project.

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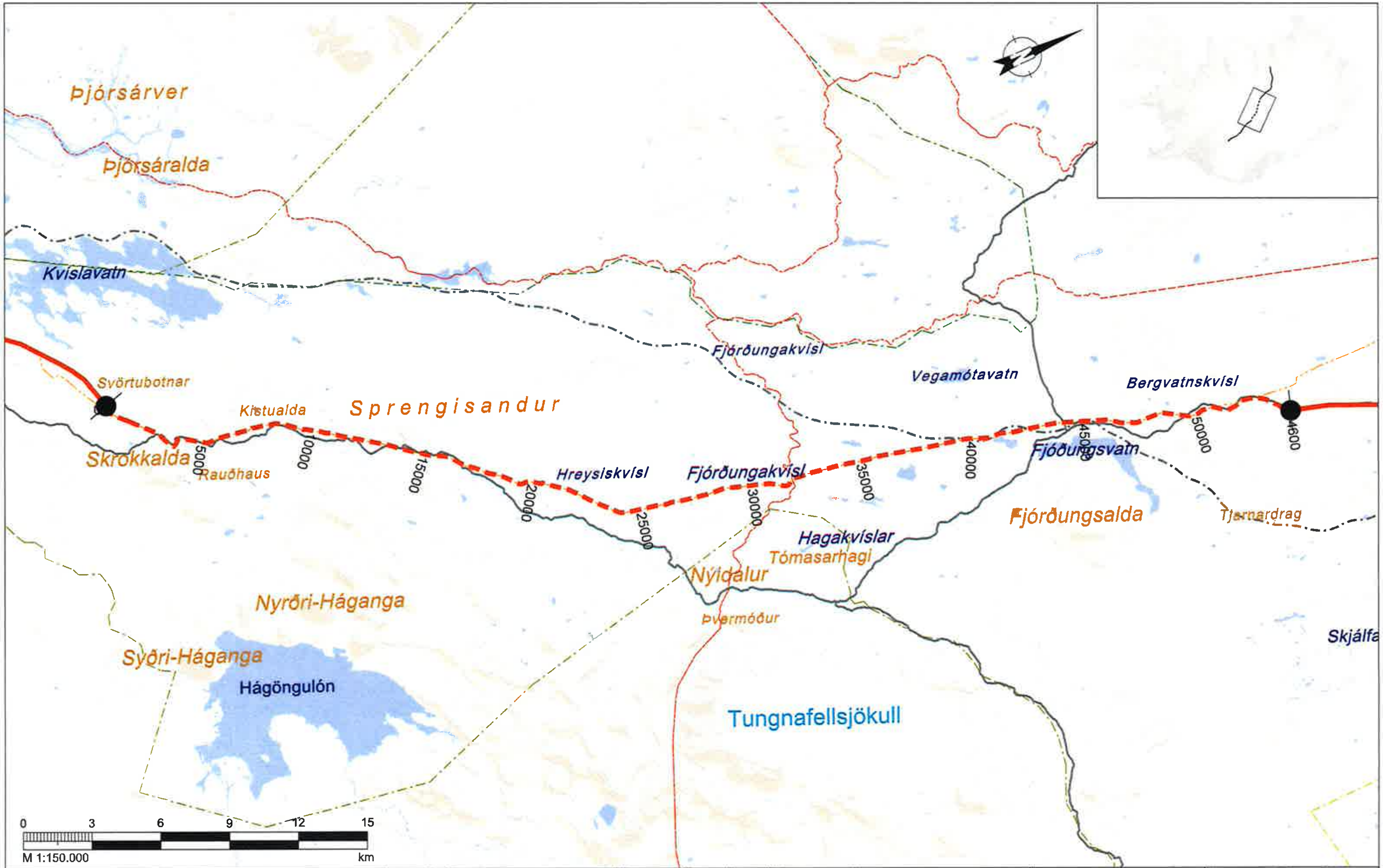
Case I
SPRENGISANDUR

2509-337-4_21_002
Overview map
Case II
EYJAFJÖRÐUR

2509-337-4_21_003
Overview map
Case III
HAFNARFJÖRÐUR



Skýringar

- Sprengisandslína - Underground Cable
- Sprengisandslína - OHTL
- Roads
- Future roads
- Proposed connection points
- Municipal boundary
- Nature reserve
- National conservation area
- Optical fiber cable
- 100m countours

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LANDSNET

OPTION AND COST FOR 132 & 220 kV UC

OVERVIEW MAP

CASE I

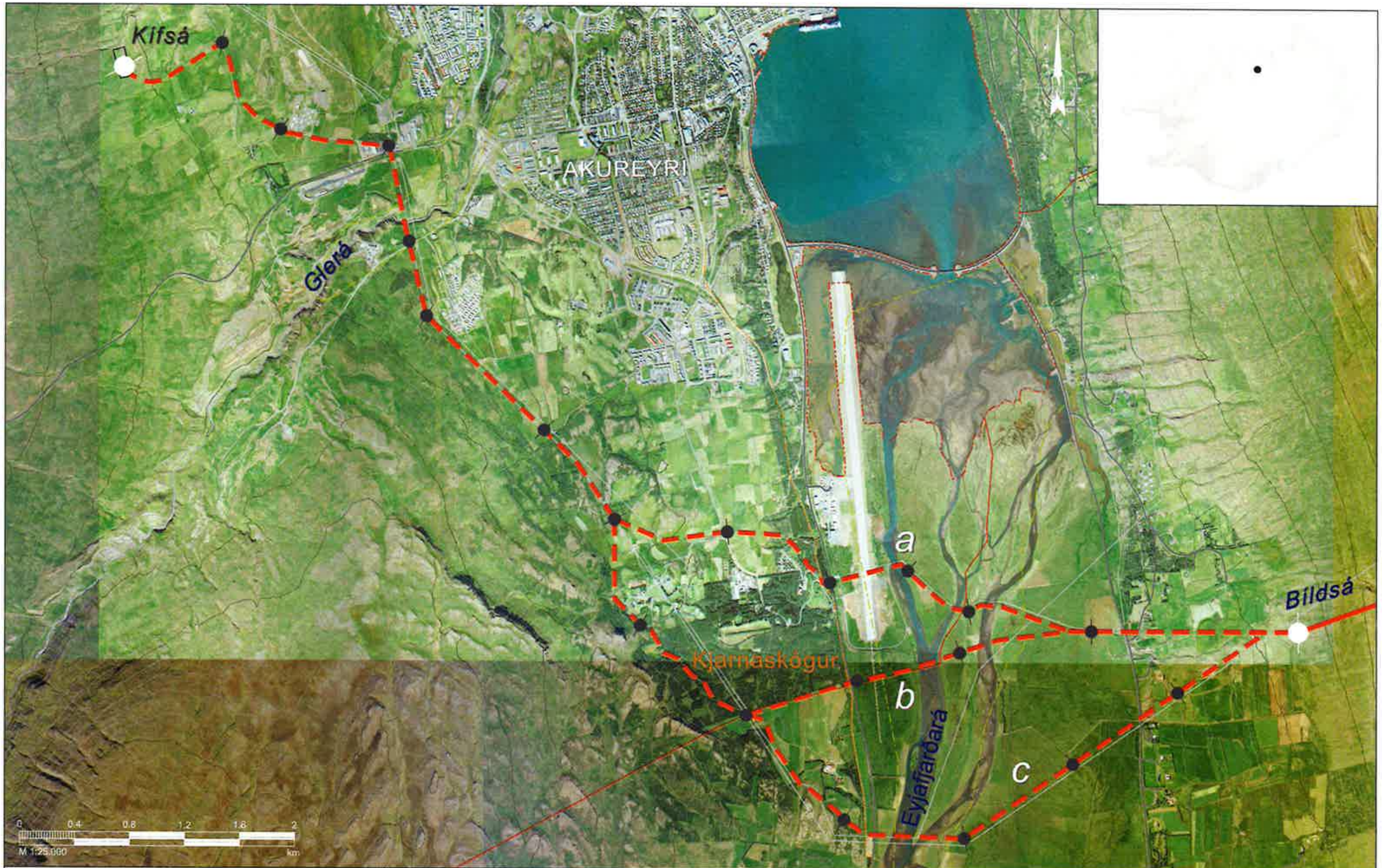
SPRENGISANDUR

EFLA VERKFRÆÐISTOFA

PROCESS	INSTALLATION	LOCATION
=	+	+

NUMBER: 2509-337

4_21_001



Skýringar

- Akureyri/Eyjafjörður - Underground Cable
- Akureyri/Eyjafjörður - OHTL
- Roads
- OHTL
- Underground Cable
- Proposed connection points
- Municipal boundary
- National conservation area
- Optical fiber cable
- 20m countours

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OVERVIEW MAP

CASE II

EYJAFJÖRÐUR

EFLA verkfræðistofa

PROCESS	INSTALLATION	LOCATION
=	+	+

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Skýringar

- Suðurnesjalína 2 - Underground Cable
- Proposed connection points
- Future roads

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OVERVIEW MAP

CASE III

HAFNARFJÖRÐUR

EFLA verkfræðistofa

2509-337

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