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Keywords climate change, electric power network, network design

Abstract

The report presents how climate will change according to climate models concerning the planning and building of electric power networks from the present state to the period from 2016 to 2045. The essential impacts of changes in weather conditions on planning and building of electric network are defined regionally based on the climate change scenarios. The importance of the effects is shown as costs and failure durations for different line structures. Moreover, the influence of the climate change on the loading capacity of the power system components is presented. On the basis of all these factors it will be judged how strong an effect the climate change has in the present electric power network and how one should be prepared for it.

The stresses of the network will increase with climate change. This will increase the number of faults in current network and at the same time the total duration of faults, if improvements for reliability will not be increased. The effect is most significant for a bare overhead line network passing through a forest in rural areas. However, it is profitable to consider the final impacts in detail, because the weather causes faults in different ways depending on environmental conditions. Principally, the impact of climate change is remarkable especially in the regions that are even nowadays sensitive to weather. Poor access to the fault locations increases the repairing time. A forest sensitive to weather conditions increases number of faults and thus the total interruption time.

Based on the calculations the influence of climate change is much lower at the roadside and even lower in the fields. Urban networks are already mostly underground cable networks having considerably lower climate effects. Increasing costs due to the climate change increases also the profitability of the investments planned for improving the reliability of the network. The profitability and sufficiency of the investment aiming at reliable distribution always need a case-specific consideration. In regions sensitive to the crown snow loads it is useful to concentrate on trimming and clearing as well as to ensure the withstand strength of line and pole structures against snow loads.

The predictions always include some uncertainty. In this work the uncertainty is assessed by the different climate change scenarios as well as by estimating how significant the calculated results are compared to the total costs. The report estimates the risk caused by the climate change.

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Tiivistelmä

Työssä esitetään, miten ilmasto ilmastomallien mukaan muuttuu sähköverkkojen suunnittelun ja rakentamisen kannalta nykytilasta ajanjaksoon 2016–2045. Ilmastonmuutosennusteiden perusteella määritetään sähköverkon suunnittelun ja rakentamisen kannalta olennaisten sääilmiöiden muutosten vaikutukset alueellisesti. Vaikutusten merkitys esitetään kustannuksina ja vika-aikoina eri johtorakenteille. Lisäksi esitetään ilmastonmuutoksen vaikutuksia sähköverkon komponenttien kuormitettavuuteen. Laskelmien perusteella määritetään, miten suuri ilmastonmuutoksen vaikutus on nykyverkossa ja miten siihen tulee varautua.

Ilmastonmuutoksen myötä verkon rasitukset kasvavat. Tämä lisää nykyverkossa vikojen lukumäärää ja samalla yhteenlaskettua vika-aikaa ellei luotettavuutta lisääviä panostuksia lisätä. Vaikutus on merkittävin maaseudulla metsässä kulkevilla avojohtoverkoilla. Lopullisia vaikutuksia kannattaa kuitenkin tarkastella yksityiskohtaisesti, koska sää aiheuttaa eri tavalla vikoja riippuen ympäristöolosuhteista. Pääasiallisesti ilmastonmuutoksen vaikutus on huomattava erityisesti nykyisin säälle herkillä alueilla. Huonot kulkuyhteydet lisäävät korjausaikaa. Säälle herkkä puusto lisää vikamääriä ja vastaavasti keskeytysten kokonaisaikaa. Ilmastonmuutos lisää luotettavuutta lisäävien investointien kannattavuutta. Näiden investointien kannattavuus ja riittävyys jakelun luotettavuuteen pyrittäessä on aina tarkasteltava tapauskohtaisesti. Tykkylumelle herkillä alueilla kannattaa panostaa raivaukseen ja oksimiseen sekä varmistaa johdon ja pylväsrakenteiden riittävä lujuus tykkykuormia vastaan.

Ennusteissa on aina epävarmuutta. Tässä työssä epävarmuutta arvioidaan vertaamalla neljän eri ilmastomallin ja päästöskenaarion yhdistelmän avulla laskettuja muutoksia. Lisäksi arvioidaan, miten merkittäviä laskelmien tulokset ovat verrattuna kokonaiskustannuksiin. Työssä arvioidaan ilmastonmuutoksen aiheuttamaa riskiä.

Preface

This research was funded by Tekes – Finnish Funding Agency for Technology and Innovation, VTT basic financing, Energiateollisuus ry – Finnish Energy Industries, Lappeenrannan Energiaverkot Oy, Pohjois-Karjalan Sähkö Oy, Lahti Energia Oy, Järvi-Suomen Energia Oy, Mäntsälän Sähkö Oy, Fortum Sähkönsiirto Oy, Koillis-Lapin Sähkö Oy, Imatran Seudun Sähkönsiirto Oy, Kainuun Energia Oy, Rovakaira Oy.

The project was a part of the Tekes technology programme ClimBus, coordinated by Jatta Jussila. The responsible project leader has been in 2006 Osmo Auvinen and in 2007 Sanna Syri, VTT Energy Systems.

The research work was performed in the VTT Energy Systems. Additionally, the effect of climate change on the cables and transformers was studied by the researched group Prof. Matti Lehtonen, G. Murtaza Hashmi and R. John Millar from Power Systems and High Voltage Engineering, Helsinki University of Technology (TKK). Senior research scientist Lasse Makkonen from VTT Structural dynamics gave valuable comments on the extreme climate conditions.

The expert group supervising the project was: Jari Eklund from Tekes, Osmo Auvinen from VTT, Jorma Väkiparta from Energiateollisuus ry (Sener), Pekka Vierimaa from Fortum Sähkönsiirto Oy and Jukka Ahonen from Pohjois-Karjalan Sähkö Oy.

We wish to thank all participating companies, the expert group and the TKK research group for making this research possible.

Espoo, December 2007

Authors

Contents

Appendices

List of symbols

AMKA	1 kV aerial bundled self supporting cable
A	present value of costs
A2	Emission scenario based on a consumer society with increasing greenhouse gases
B2	Emission scenario aiming at a sustainable development
BLX	Overhead line system insulated with XLPE (from Norwegian words: Belagt Linesystem)
CH_4	Methane
CO_2	Carbon dioxide
Delayed AR	Delayed auto-reclosing
ECHAM4-OPYC3	Climate model
f	number of interruptions for a customer in a year
HadAM3-H	Climate model
High speed AR	High speed auto-reclosing
i	rate of interest
IPCC	Intergovernmental Panel on Climate Change
$k, k_1, k_2,. ..k_n$	yearly cost
k_e	interruption cost valuation, energy
k_p	interruption cost valuation, power
K	load factor
KI	Flat, fuse 1 x 25 A, no electric stove, consumption 2 000 kWh/year

K2	Single house, fuses 3 x 25 A, electric stove, consumption 5 000 kWh/year
KAH	Outage cost, interruption price (keskeytyksen aiheuttama haitta)
L1	Single house with direct electric heating, fuses 3 x 25 A, consumption 18 000 kWh/year
L2	Single house with partly accumulating electric heating, fuses 3 x 25 A, consumption 20 000 kWh/year
MOA	Metal oxide arrester
M1	Agriculture, plant growing, fuses 3 x 35 A, consumption 10 000 kWh/year
M2	Agriculture, livestock farming, fuses 3 x 35 A, consumption 35 000 kWh/year
n	time of payment, frequency of faults
N_2O	Nitrous oxide
ONAF	Transformer cooling method: oil natural, air forced
ONAN	Transformer cooling method: oil natural, air natural
OPEX	Operative expenses
P	average consumption of a consumer group
PAS	Overhead line system insulated with XLPE (abbreviation from Finnish words: päällystetty avojohto suurjännitteelle)
P_{50}	50-year return values
R	ratio of load losses at rated current to no load losses
RCAO	Rossby Centre Regional Atmospheric-Ocean Model
RCA	Rossby Centre Regional Atmosphere Model

RCO	Rossby Centre Regional Ocean Model, Baltic sea
S	Yearly cost
SAIDI	System Average Interruption Duration Index, h/customer
SAIFI	System Average Interruption Frequency Index, number/customer
t	Interruption time of a customer in one year
T1	Small-scale industry, consumption 150 000 kWh/year, demand 75 kW
T2	Small-scale industry, consumption 600 000 kWh/year, demand 200 kW
T3	Medium-scale industry, consumption 2 000 000 kWh/year, demand 500 kW
T4	Medium-scale industry, consumption 10 000 000 kWh/year, demand 2 500 kW
TKK	Helsinki University of Technology
VTT	Technical Research Centre of Finland
λ	number of fault interruptions of a customer in one year
ρ_s, ρ_{dry}	thermal resistivity of the soil and thermal resistivity of the dry soil
θ_H	hot spot temperature of a transformer winding
$\Delta\theta_H$	hot spot temperature rise over top oil temperature
$\Delta\theta_{T0}$	top oil temperature rise over ambient

1. Introduction

Due to human actions the emission balance of the globe is changing. This will together with natural and other non-human causes lead to a climate change. As a consequence of the climate change strong phenomena have been predicted to occur in Finland, too. According to the climate model scenarios the changes will be clearly seen already within 40 years i.e. during life time of the present electric power networks.

The climate change is known to affect significantly the power system. The subject has been studied in a VTT project called *Impacts of climate change on electricity network business* [1]. The goal in the project was to form an overview of the climate change and its influence on the power systems and network business. The most challenging impact is the increase of failures.

Tekes, the Finnish Funding Agency for Technology and Innovation is running a technology programme ClimBus to mitigate climate change. Both these projects are included in that programme. This report continues the earlier project and utilizes the large information files concerning the climate change models and scenarios that VTT has obtained. The main goal is to clarify the overall requirements for the planning and building processes of the electric power distribution networks. This project concentrates on the climate change impacts mainly on the medium voltage distribution system. The periods under examination are the control period 1961–1990 and the period 2016–2045.

The medium voltage distribution network in Finland has mainly been built during years 1950 to 1970. Main part of those lines is bare overhead lines in rural areas, often in forests and sensitive for failures. A general line structure is bare overhead conductors on impregnated wooden poles. In several areas the wooden poles are in the end of their lifetime and those parts of the electric network are coming to renovation phase. In conjunction with rebuilding there is a good opportunity to improve the reliability of the distribution. Different weather conditions are the main reasons for failures in network and along with the climate change these conditions increase the stresses according to the climate models. Essential factors in planning investments are the requirements given for the electric network in the future. If climate change effects are ignored the network may not necessarily offer the required reliability in the climate conditions in the future. It is possible to decrease failures and fault duration in some regions using reliability increasing investments in spite of the climate change, but the goals set will not necessarily be achieved. Then in the worst case the large-scale investments have to be performed. This project aims at supporting the decision-making for investments considering the climate change in the distribution network.

Chapters 2 and 3 present briefly background information about Finnish power electric network and the planning and building processes. The present situation in considering the climate change in the electric network business is described in Chapter 4. The next chapter introduces the essential scenarios of the climate variables and studies the effects of changes regionally. In Chapter 6 the influence of climate change is regarded as costs and failure duration. Helsinki University of Technology (TKK) Power Systems and High Voltage Engineering has estimated the effects of climate change on some power system components. The results are given in Chapter 7. The project results are analysed in Chapter 8, and Chapter 9 summarises the project results. The results of this project are intentionally presented on a general level because the real costs and failure duration depend strongly on case-specific parameters.

2. Description of Finnish Electricity Network

2.1 General view

The primary goal of the electricity network system is to meet the electricity production and consumption. Another goal is to transfer electricity from power plants to customers with good enough quality and as cheaply as possible.

The Finnish electricity network can be divided into three levels: the transmission grid, regional networks and distribution networks. Figure 2-1 shows the overall structure of the Finnish electricity network.

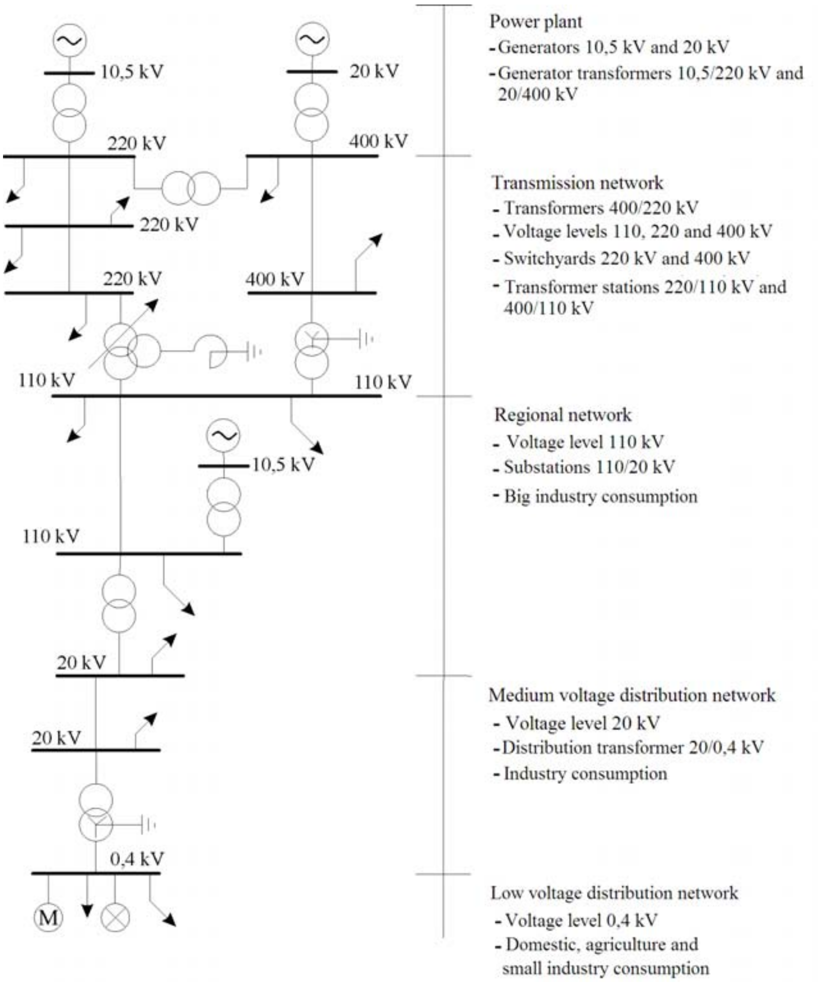

Figure 2-1. The overall structure of Finnish electricity network.

The transmission grid consists of 400 kV and 220 kV transmission power lines and the most important 110 kV lines as well as 400/220 kV, 400/110 kV and 220/110 kV substations. All remarkable power plants have been connected to the transmission grid. The transmission grid is owned and operated by the Fingrid Ltd. Regional networks usually operate at 110 kV voltage level. A distribution network consists of substations, medium voltage lines (6 kV–70 kV), distribution transformers and low voltage networks (0,4 kV).

There are in summer 2007 about 90 distribution companies in Finland. The networks owned by these companies vary considerably in size and operational environment. The smallest company has around twenty kilometers of power lines, while the largest has over 60 000 km. Most electricity users are connected to a distribution network. A distribution network consists of medium voltage and low voltage networks.

2.2 Conductor types of different voltage levels

1) Networks of 45 kV or over

In the year 2005 Fingrid Ltd has 3982 km of 400 kV lines, 2330 km of 220 kV lines and 7588 km of 110 kV lines. These all are overhead lines typically with steel reinforced aluminium conductors. In special cases underground or sea cables have been used. In addition, Pohjolan Voima Oy and some other regional transmission network operators own both 220 kV and 110 kV lines [2]. Because these transmission lines are under special care due to their importance no matter what the climate change is, we do not enlarge upon these lines more.

2) Medium voltage network

Medium voltage network is three-phase and the voltage level is normally 20 kV in Finland. Some city areas and some industrial networks have 10 kV networks, too. The length of medium voltage network is about 140 000 km. Medium voltage network is interconnected in essential parts, but it is used radially. The connections are mainly done using disconnectors. Radial networks are very common in rural areas. Reliability is much better in an interconnected network because in that case there is more than one possible supply connection point. Interconnected networks are used mainly in urban areas. Figure 2-2 shows the proportion of different conductor types in the medium voltage network.

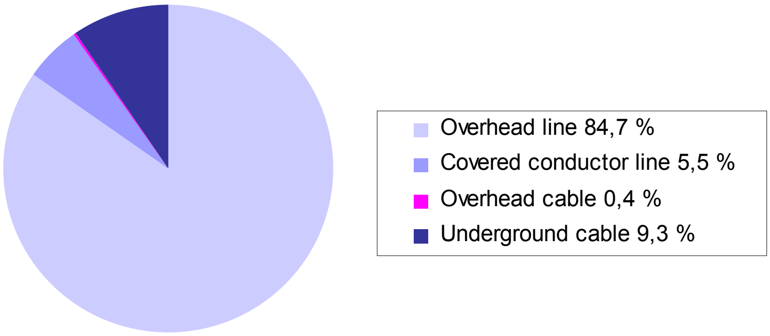

Figure 2-2. Proportion of different conductor types in the medium voltage network, data from the statistics of 2006 [6].

The most common medium voltage network configuration is an overhead line. Overhead lines are usually built by using steel/aluminum conductors and wooden poles. Aerial cables are rare. Much more common conductor type is a covered conductor (PAS, BLX). Covered conductors are categorized as overhead lines.

Underground cables are very common in urban areas. Environmental factors and lack of space for right of ways are the most important reasons.

3) Low voltage network

Low voltage network is also three-phase and the voltage is 0,4 kV. The three-phase system is preferred because of the relatively high loads. Losses are six times higher in a one phase network than in an evenly loaded three-phase network in the same cross-section conductors. The protection is based on the fuses. Basics of the configuration are the same as in the medium voltage network: radial networks are very common in rural areas and interconnected networks are used in urban areas. The length of low voltage network is about 220 000 km. Figure 2-3 shows the proportion of different conductor types in the low voltage network.

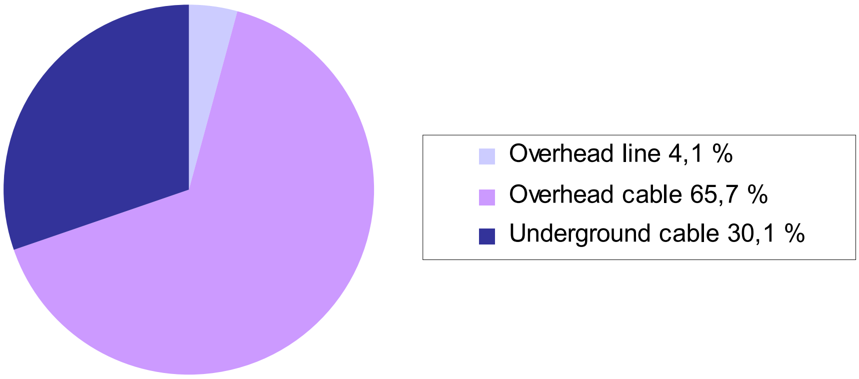

Figure 2-3. Proportion of different conductor types in the low voltage network, data from the interruption statistics [6].

AMKA aerial bunched cable is the most common conductor in the low voltage network. Underground cable is another remarkable conductor in the low voltage network. Underground cable is very common in urban areas where the environmental factors and lack of space for the most suitable routes are the most important reasons for cabling. There the proportion of overhead lines is very small and overhead lines are supplying in the low voltage network.

3. Planning, design and building process

The present-day planning process of electric power networks is described here in a quite simplified manner. The description of the planning process concentrates on the topic of this work. More detailed design information is given for example in the reference [5].

The purpose of the process is to plan and design a new power line for a new consumption unit or to rebuild the old network parts according to the requirements. The basic principles in planning new lines or rebuilding networks are almost similar. In Finland the existing electric network covers practically all the inhabited areas and that is why planning is focused mainly on rebuilding.

The needs for rebuilding the network are determined by computer-based calculations and inspections. Calculations may include electric power quality in different parts of the network. Periodic inspections cover wooden poles, distribution transformers and other network components. Aging of the components, increased power demand, poor power quality or needs for dividing distribution areas often lead to rebuilding or reinforcement. The aim of the planning is to choose structures and routing of power lines so that life cycle costs are minimised. This applies to both building new lines and rebuilding. Boundary conditions need to be considered.

Investment, maintenance, outage and operation costs are taken into account in the life cycle costs. The investment costs consist of all building costs including materials and machines. Maintenance includes inspections, service and clearing the line routes. Failure costs cover repairing the fault as well as outage and fixed compensations. The outage costs are used for estimating disadvantages or damages resulting from interruptions. The investments for increasing reliability of the network can be compared using the outage costs. At this moment, the outage costs are not real for utilities and these costs are not necessarily used in investment calculations. The operational costs include losses, personnel, facilities and spare part supplies.

Requirements for electric power quality, aesthetic characters, and permission aspects are among other things the boundary conditions for the final solution (structure and route). The boundaries can have a significant influence on the investment and its costs. The utility may for instance have a certain limit for outages to a certain customer and fulfilling that requirement may cause heavy investments.

Depending on the operating principles of the utility and the project itself the costs can be defined using a life cycle model based on all previously mentioned costs or based on the bare investment costs. Typical consumption density in rural areas is often so low that the profitability can be estimated by investment costs, only. Wider study will not give more alternative structures. In that case the investment study means comparison of the different routes. The final solution is usually more or less a compromise. For example, due to permission aspects, the line can rarely be built exactly following the planned route. Compulsory purchase is possible but in that case construction will be delayed and the network company can get negative image. Great uncertainties in the life cycle costs of electric power network prevent the perfect solution in the planning and design. The electric network can be long-lived, 40 years or even more, so it is not possible to define all life cycle costs of electricity network. For example it is impossible to calculate losses exactly.

Guides for planning the electric network are based on common practice and/or instructions, so called network policy. Not all companies have a written policy but each company has a common practice for planning instructions. The requirements are clearly stated in the instructions thus regulating and controlling the network structure. Certain goals can be set for the reliability. One parameter describing the reliability of the distribution is called SAIDI (System Average Interruption Duration Index, h/a).

The planning process can be divided into three phases: general planning, computer based planning and field planning. Differences between the phases are not clear depending on the procedures of the companies. The functions in each phase are described in the next Sub-Clauses. Only general features are described because companies' operations models deviate from each others. For example field planning can include also construction planning.

3.1 General planning

The complete medium voltage distribution network, i.e. large entity, is studied in the general planning phase. Long-term planning is an essential part of general planning. Its main purpose is to determine what kind of investments are needed and when they should be done.

The existing network provides a starting point for planning. Province plan and master plan areas as well as population forecasts are utilised for finding out how power consumption and focused areas in consumption are changing. Population forecasts do not always give the totally right vision. There are areas in Eastern Finland where population decreases but the number of consumption points and consumption of electricity increase. The number of consumers increases mainly with week-end cottages and the total power demand with the increasing number of electric heating and other electrical appliances.

Changes in the focus area of consumption and the distribution network properties required in the future will demand development of the network. Big investments having a wide influence on the network are examined in the general planning phase. Among other things the following issues shall be inspected: where to build 110 kV transmission lines (regional network) and 110/20 kV substations. Moreover, important cases for consideration may be reserve power supplies and the main lines. Sites are allocated for substations and electricity lines when needed. These investments require careful consideration taking into account financial and electrotechnical factors.

3.2 Computer based planning

Computer based planning will be started when there is a need to build a new network branch or rebuild an old network. The forests, roads, rivers, lakes and fields are known by the geography. The areas are separated into city areas, urban areas, rural areas as well as river and lake regions. The structures (overhead line, covered conductors or underground cable etc.) are defined, a proposal or proposals of route are formulated and electrical dimensioning is designed in a computer based planning phase.

In the city areas, planning of structures and routes do not have many alternatives. Transformers and lines will be built in the areas reserved for them in building plans. The lines are mainly underground cables. The transformers in the city areas are normally located in transformer substations or in building transformers. Underground cables are used because there is no space for the overhead lines and distribution is more reliable in underground networks than in overhead line networks. Planning methods are quite similar in urban areas but there are also other possibilities for structures like overhead lines and pole mounted transformers.

In rural areas, there are basically lots of possibilities for structures and routes. On the grounds of life cycle cost the most suitable construction and route in a certain area can be chosen. The higher the power consumption on the feeder line is, the better network quality is profitable. The reliability of the network can be increased by using covered overhead lines and/or by building the roadside lines. The location and the number of disconnectors or light circuit breakers have a significant effect on the network operation. Carefully planned placements of those devices can shorten the outages. Generally, there are a number of different technical and economical solutions for improving reliability of the distribution. Chapter 4 presents the most used solutions for increased reliability.

Computer based planning gives a draft proposal for routes, configurations and electrical dimensioning including voltage drop and short circuit capacity calculations.

3.3 Field planning

The computer based network plans form the basis for field planning aiming at an appropriate line position in the terrain. The goal is to minimise the disadvantages caused by the line construction and structures as well as mounting the line perfectly in the terrain.

During the field planning a suitable route for the line will be searched. Not all local circumstances, like obstacles or landowners' wishes, have been possible to be studied on the map. Field planning includes conversations with landowners and applications for permissions of line construction.

In city centres and other urban areas field planning phase is essentially simple. Overhead lines are used also in urban areas if underground cables are hard to be built for example because of rocks. The aim is to put conductors in the same trench with telephone cables and water pipes etc. In city centres lack of park areas can cause problems because it can be hard to find place for transformers.

In rural areas, the original plan usually changes in the field planning phase because of the permissions for land use and the aesthetic characters. Permission aspects and environmental values are emphasized in areas, where there is a lot of recreational use. In consequence of permission aspects, the final route and structure is more or less a compromise.

In the field planning phase the possibilities of the line building must be taken into account. It is not worth planning an electric power line into a terrain, where contractor's and utility's vehicles cannot move. In an overhead line network, the possibility for integrated use with low voltage aerial cables must also be observed. Remarkable savings can be achieved in cable digging and ploughing, if telephone cables etc. are mounted at the same time. These kinds of aspects must be paid attention to. Experienced field planner will see vulnerable areas for failure and can suggest changes into the original plan. For example, an aerial cable can be suggested instead of an overhead conductor.

In rural areas the overhead lines built across the fields would be best solution in preventing the failures. But sometimes it is hard to get building permissions. In that case, lines are erected next to the fields or in roadsides.

In the river and lake regions, the aesthetic characters are emphasised and building permissions are harder to get. As a consequence of that the conductors are very often cables. Repairing the faults in water cables can take long time and that is why the routes and structures are planned very carefully.

An experienced planner can see the entirety of an electricity network and can plan structures both expanding the network and reducing failures. The goal of the field planning is to confirm structures and routes of electric networks. All structures like places and lengths of poles, locations of transformers and disconnectors, stay wires etc. shall be exactly marked on the ground. Also trees and other barriers are removed in field planning phase.

3.4 Building process

The building process can be started right after the field planning is completed. The building will be done by the own company or as a purchased service from the outside contractor(s). Materials are ordered in accordance with the design documents and the implementation of work is planned. The process includes confirmation of orders, allocations and the planning of the work itself depending of the progression of the building in company. Essentially, the building process follows the next description.

Licenses of transport are provided for roads and ground, if needed. For example, one is not allowed to go to fields anytime. In case of a soft soil the poles are erected when the ground is frosted whereas the cables have to be ploughed during the no-frost season. Using all-round vehicles (excavators, tractors) the construction work can be carried out regardless of the season. However, it may be difficult to get the landowners' permissions for erecting poles at the no-frost season, because the heavy machines leave deep traces on the soft soil. After the obtaining permissions for transporting, materials are delivered to the construction site to the places pointed out by the planner.

Planning of the outages is an important part of this phase. Only few outages with a restricted duration are allowed. Planners must take into account special requirements. Reserve power can be used if needed. For instance the customers shall be informed of the outage three days before the power interruption. The scheduling of construction work has a big effect. If for some reason (hardware failure, thunder and too low temperature) the work cannot be finished by the deadline, this causes a delay of several days to the working, because the customers must be informed of a new outage time. The aim is to avoid the outages and a construction work can be carried out even with the live working, if possible.

4. Climate factors in the current business activity of electric power systems

4.1 Climate change, its impacts and some preventive measures

Climate conditions are nowadays the most remarkable reasons for failures in power systems. As an example, Figure 4-1 shows reasons for failures in medium voltage distribution network in 2006. The most difficult weather conditions for the reliability of the distribution are heavy winds, snow and thunder. Those conditions can cause very wide and slowly repairable faults. Careful planning of power networks may reduce failures and their duration. All disturbances in distribution caused by weather conditions cannot be removed.

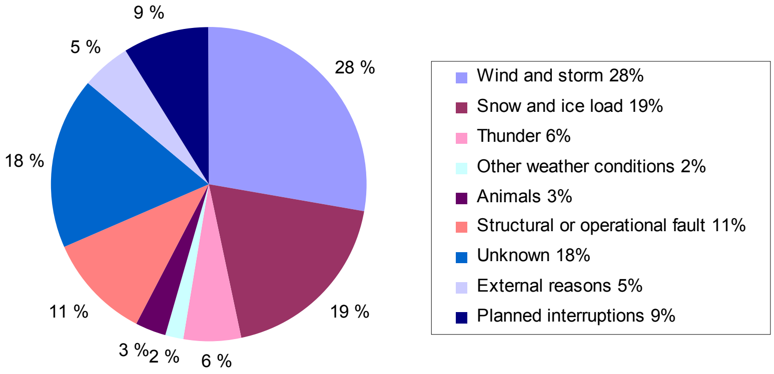

Figure 4-1. Reasons for failure numbers of the customers in 2006, data from [6].

The failures caused by the climate are problematic mainly in rural networks. City and partly urban networks usually consist of underground cables in which the stresses due to climate are much lower than in rural networks. There are overhead lines in the urban areas, too, but the fault locations can be reached quickly. The reserve supplies in circular network structure often shorten significantly the fault duration. The building plans require mostly underground cables in city and urban areas. This leads to a reasonable alternative, as the construction costs per consumer are acceptably low due to high consumption density.

The increase of small animals or particles, which the climate change can cause, may have a remarkable effect on the failure rate. The increasing number and staying times of the passage birds near the overhead lines most probably cause an increasing number of short duration interruptions. Small gnawers are capable of destroying the insulation material or the wooden structures. A high pollen content or a swarm of insects can reduce the withstand capability of the insulators. Another influence of the climate change may be the transboundary pollution like carbonic or sulphuric acids. This kind of pollution will increase the corrosion of the metal structures. All these events tend to increase the maintenance costs.

The network structures to be built in rural regions depend strongly on consumption density and terrain. The investment costs of the covered conductors are much higher compared to those of the bare conductors. The decreased maintenance cost will not cover the difference in economical considerations. Companies want to increase the reliability of distribution, but a large scale over dimensioning is not profitable. A long line through a forest with a small and scattered consumption is a challenging object for reducing interruptions and their duration.

Many solutions aim at reducing failures and outage times caused by difficult climate conditions. Some of them are taken into account already at the general planning phase, but the detailed design is obtained in the computer based planning and field planning phases. In the following the commonly used measures increasing the reliability of distribution are listed and commented:

- Substation
  - \+ Divides efficiently the distribution areas into smaller parts and thus increases excellently the reliability of the distribution.
  - \+ Special low cost substations with a lightweight structure are under development.
  - \- Expensive.
  - \- Increases short circuit currents in distribution network.
  - \- 110 kV transmission line may be required depending on location.
- 1 kV system
  - \+ Low power and often fault sensitive medium voltage branch lines can be changed into 1 kV system in order to achieve higher reliability in distribution.
  - \- Increases the number of transformers.
  - \- Leads practically into new network topology.
  - \- Practical experience is still limited.
- Moving lines to roadside
  - \+ Purpose is to move lines situated in forests or other vulnerable locations into more safe routes.
  - \+ Increases working reliability and makes maintenance and repair work easier.
  - \+ Total length of the line may be longer, but the investment costs do not normally exceed the costs of the line in terrain. This is especially valid with high compensations for the land use.
  - \- Obtaining a building permit may be difficult.

- Covered conductor lines (PAS, BLX)
  - \+ The momentary touching of covered phase conductors between each other does not lead into a short circuit.
  - \+ Birds, branches and sticks flying on the lines do not cause high speed or delayed automatic reclosing and thus do not cause a short interruption. Thus, the operational reliability is better than in a case of a bare overhead line.
  - \+ Phase-to-phase spacing is short which allows smaller lane widths, especially in double lines. Thus a good application is for instance the use of the multiconductor lines from substations.
  - \+ Good structure in regions with crown snow-load.
  - \- The lines have to be checked always after storms. Protective system does not necessarily detect trees leaning on the conductors. Actually, there have been cases when the protection has not detected even a broken conductor.
  - \- Branches and trees scrubbing the conductors may damage the conductors and insulating materials, too. During a long time this will cause surprising faults that are difficult to repair.
- Aerial cable
  - \+ Withstands the stresses caused by birds, branches and sticks. Decreases a number of high speed and delayed automatic reclosing.
  - \+ No interruptions even though a tree is leaning on the conductor.
  - \- The lines have to be checked always after storms. The protective system does not necessarily detect tree leaning on the conductors.
- Underground cable
  - \+ Prevents the failures caused by storms and crown snow-load i.e. the large scale malfunction.
  - \- No practical experiences on withstand ability in rural areas: How roots of the trees and stones might affect the insulation material and thus the possible failure of the cable?
  - \- Repairing the faults takes along time. In practice a reserve supply is needed.
  - \- Expensive: the cable mounted in rural areas costs double the cost of the bare overhead line.
  - \- Increases the earth fault currents and capacitive reactive power.
  - \- Difficult and expensive to modify the network afterwards.

- Direct current distribution systems
  - \+ Cabled system can prevent the failures caused by storms.
  - \- Converter stations are still expensive.
  - \- Reactive power has to be produced for the converters.
  - \- Breaking of the direct current is difficult and circuit breakers are expensive.
- Disconnectors with a remote control
  - \+ Possibility to disconnect the fault location quickly and shorten the outages.
  - \- If uncovered there is a freezing risk leading to unreliable operation.
- Pole-mounted circuit breakers
  - \+ The failure after the circuit breaker does not cause total interruption (permanent, high speed or delayed automatic reclosing) to the customers before the circuit breaker. It reduces the outage duration as well as the number of high speed or delayed automatic reclosings.
- Reserve connections
  - \+ Adding a supply connection decreases outage duration in fault cases. They can possibly reduce the number of interruptions during maintenance and building networks.
- Compensation of earth fault current
  - \+ Decrease earthing voltage
  - \+ Number of momentary distribution interruptions will reduce, because extinction of arcing earth faults without operation of protective devices.

Additionally, the reliability will be increased by protecting the transformers with devices not causing interruptions, like metal oxide arresters (MOA) as well as by adding automated control systems, different fault location applications and reserve capacity. Changing pole-mounted transformers into secondary substations have also been planned and realized.

All previously mentioned items improve the reliability in certain points of the distribution network. A common negative side for all these solutions is that they increase investment costs. That is why for example all manual disconnectors cannot be built to operate with remote control. The price in one disconnector case is about four times higher than the price of a manual device [4]. Cost-effectiveness of the previously mentioned structures is always case-specific and depends mainly on network topology, consumption and power quality requirements. In that case a good functional solution consists of several different techniques. It is not reasonable to concentrate only on one structure improving the reliability.

Additionally, the reliability of distribution will be improved by making maintenance more effective. Forest workers are trained to observe and remove the trees dangerous to distribution lines. The number of inspections, like monitoring by a helicopter, will be increased.

The damages caused by crown snow-load will be reduced by observing snow thickness and by making preparations for removing the snow-loads. Public observations about snow loads on the trees close to the lines can be asked by means of newspapers, radio and internet. Risky trees will be felled and snow removing will be started even before failures have occurred. The companies have prepared for large scale failures or disasters by different co-operation agreements with local forest workers, forest machine owners and neighbouring utilities.

Climate is not the only reason for faults. Preparation for failures due to climate conditions gives normally the operational reliability in case of other failures, too. The optimal operation has to be taken into account during the planning phase. Reserve supply routes may be useful also in maintenance.

The planning has to consider faults and also the stresses due to climate conditions. Essential stresses taken into account in dimensioning the overhead lines are snow and ice loads. Shorter distances between poles and expanded cross-arm structures are used in areas with crown snow-load. Shorter spans help in decreasing the snow and ice loads of the cross-arms, conductors and insulators. Heavy wind can swing the snowy and hanging conductors such as the conductors touching each other causes short-circuit. The faults may be prevented by using expanded cross-arms, which increase phase-to-phase spacing.

4.2 Regional differences in failure characteristics

Finland is a long-distance country in north-south direction, thus, both climate and terrain differs between Southern and Northern Finland. That is why also failures and other stresses caused by different climate conditions vary from region to region. Weather conditions like temperature, wind, precipitation and thunder storm each have an influence on faults. Other essential conditions are height from sea level, topography, water systems, soil and wood species. Tables 4-1 to 4-3 present the characteristics of interruptions due to faults in rural utilities from 1998 to 2003. Figure 4-2 shows the regional division used in these tables.

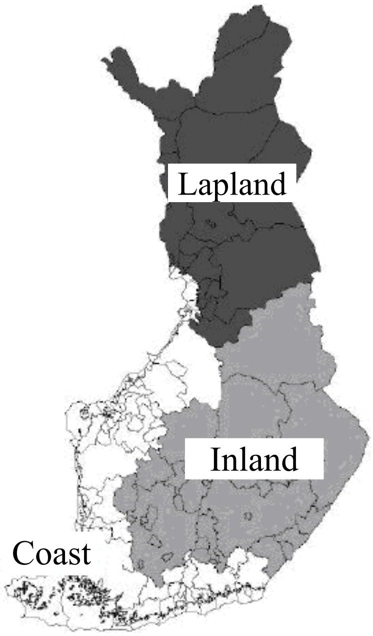

Figure 4-2. Division of area, the interruption statistics in 2003 [6].

The abbreviations in Tables 4-1 to 4-3 are:

λ number of fault interruptions of a customer in one year [events/a]
t interruption time of a customer in one year [h/a],
n fault frequency [events/100 km].

Table 4-1. Average values of fault interruptions in rural areas from 1998 to 2003 [6].

	λ [events/a]			**t [h/a]**			**n [events/100 km, a]**		
	Coast	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**
Wind and storm	0,90	2,61	0,40	1,27	3,36	0,42	2,25	3,29	0,46
Thunder	0,21	0,35	0,30	0,18	0,43	0,26	0,55	0,57	0,39
Snow and ice load	0,05	0,22	0,22	0,04	0,21	0,20	0,11	0,34	0,24
Tree fallen by snow load	0,20	0,60	0,10	0,43	0,54	0,08	0,49	0,91	0,10
Other weather conditions	0,05	0,06	0,05	0,04	0,04	0,03	0,13	0,08	0,04
Weather total	1,42	3,84	1,07	1,96	4,57	0,98	3,51	5,18	1,23
Other reasons total	0,85	1,24	1,06	0,48	0,58	0,67	2,49	2,28	1,39

Table 4-2. Maximum values of fault interruptions in rural areas from 1998 to 2003 [6].

	λ [events/a]			**t [h/a]**			**n [events/100 km, a]**		
	Coast	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**
Wind and storm	1,23	6,04	0,55	3,21	6,59	0,84	2,95	6,06	0,73
Thunder	0,27	0,60	0,46	0,25	0,86	0,47	0,66	1,01	0,70
Snow and ice load	0,10	0,43	0,40	0,11	0,44	0,42	0,27	0,61	0,54
Tree fallen by snow load	0,47	1,18	0,24	1,28	1,22	0,18	1,26	1,67	0,31
Other weather conditions	0,07	0,10	0,12	0,05	0,07	0,06	0,15	0,14	0,09
Weather total	2,14	8,35	1,77	4,90	9,18	1,97	5,29	9,49	2,37
Other reasons total	1,10	1,91	1,67	0,62	0,71	0,97	3,28	4,43	2,22

Table 4-3. Minimum values of fault interruptions in rural areas from 1998 to 2003 [6].

	λ [events/a]			**t [h/a]**			**n [events/100 km, a]**		
	Coast	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**	**Coast**	**Inland**	**Lapland**
Wind and storm	0,60	1,42	0,26	0,63	1,73	0,17	1,53	2,18	0,28
Thunder	0,13	0,26	0,15	0,11	0,26	0,13	0,40	0,45	0,20
Snow and ice load	0,02	0,05	0,06	0,01	0,04	0,05	0,06	0,07	0,05
Tree fallen by snow load	0,05	0,08	0,02	0,04	0,07	0,02	0,10	0,12	0,01
Other weather conditions	0,04	0,03	0,02	0,02	0,01	0,01	0,09	0,04	0,02
Weather total	0,84	1,84	0,51	0,81	2,11	0,38	2,18	2,86	0,56
Other reasons total	0,65	0,91	0,67	0,34	0,48	0,52	1,84	1,58	1,08

Failures caused by various weather conditions are most common in inner parts of Finland and rare in Lapland according to the presented statistics. Clear differences can be seen in interruption characteristics of these regions: the maximum values of Lapland are less than the minimum inland values. The values of *weather total* are in inland four times higher than in Lapland. Remarkable differences can be found in characteristics describing *wind and storm* (including thunder storms) and *tree fallen by snow load*. In both failure cases the final reason has been the trees growing near the conductors. In recent years Lapland has not encountered strong storm fronts and this is of course a remarkable reason for smaller number of fault interruptions in Lapland. The storm named *Mauri* in 1982 was the latest strong and large scale storm in Lapland. There are other factors reducing the damages caused by fallen and bending trees. The forests and wood species differ from those in other parts of Finland. A pine is the dominating coniferous tree in Lapland. This is important as the fir tree is one of the main wood species which easiest fall in the wind. Lapland's growing timber tree has been adapted to considerably heavy snow burden, e.g. candle spruce. The terrain is mostly weakly growing and production forests are less common compared to inland.

The maximum values of coastal regions and inland were obtained in 2001, during the storms called *Pyry* and *Janika*. Finnish Meteorological Institute reported in [8] that storm *Pyry* caused highest damages in western and southern Finland while storm Janika in Pirkanmaa, Häme, Itä-Häme and Uusimaa. The day after storm *Janika*, large scale storm damages still occurred especially in Middle Finland, in neighbouring municipalities of Lake Päijänne and in Uusimaa. Other extremely heavy storms have been *Unto* in summer 2002 causing damage in Savo and *Rafael* in December 2004 in Southern Finland. Generally, heavy winds felling trees occur yearly with thunder. However, they occur in a comparatively small area. Rapid flows developing during thunder storms may be very forceful, but typically the affected zone is small.

Figure 4-3 shows how the total lengths of the overhead lines and the cables have been changed in the medium voltage network during 1998–2006. One has to notice that the statistics do not include the year 2004. Not all utilities have answered yearly, which cause some uncertainty. No logical values for the length of overhead lines in the forest were available and those values are not shown in Figure 4-3. No clear trend can be seen in the proportion of the overhead lines and the fault density. The previously mentioned storms *Pyry* and *Janika* explain the peak in the 2001 failure density curve and year 2006 was also a stormy year.

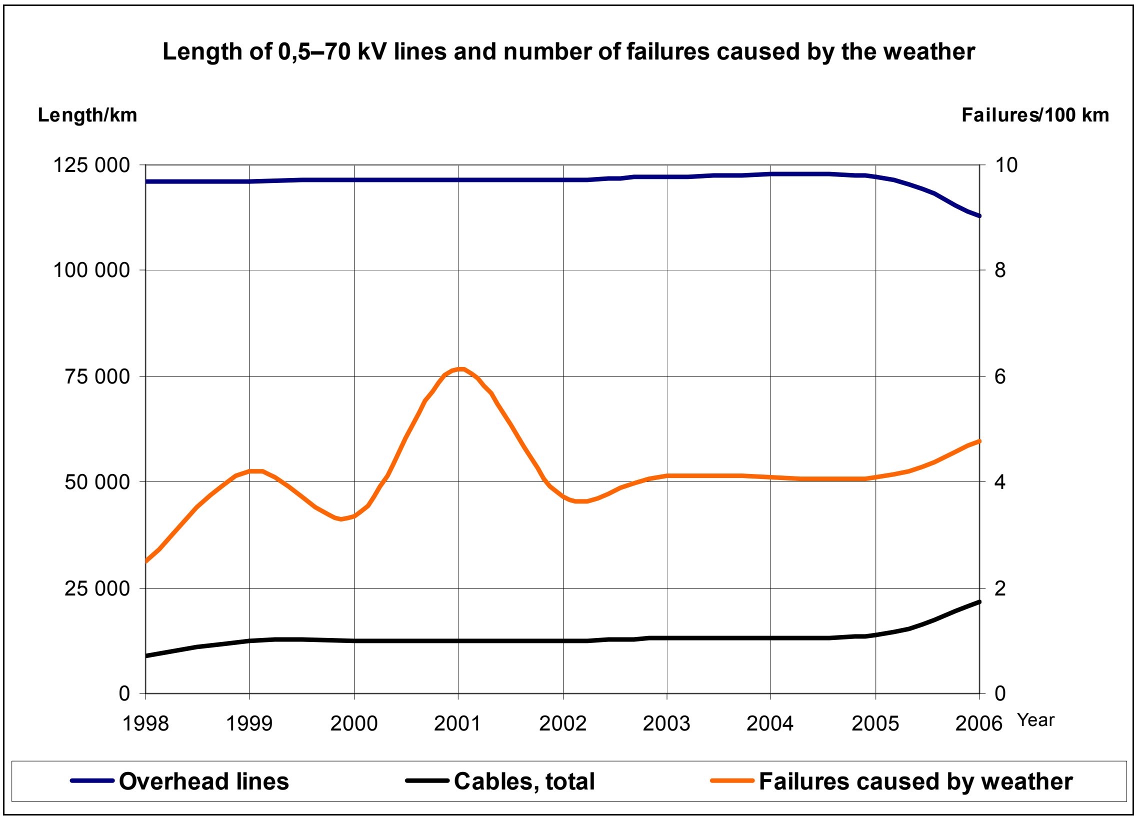

Figure 4-3. Total length of medium voltage distribution lines in 1998–2006 and the failure density caused by the weather condition, the statistics has been taken from [6].

Besides strong winds another weather condition is crown snow-loads which can cause extensive interruptions. This condition can be developed in two ways: either by hoar frost or by ice, wet snow and snowfall. The hoar frost event starts with small super cooled droplets falling to conductors and branches and freezing at the same time into frost crystals. When the trees carry a heavy crown snow burden, they can bend on the line. Especially slim broadleaf trees easily bend under snow load. Those trees also tend to be fallen due to wind. Snow burden generated by hoar frost typically appears in the hills of Vaara-Suomi (Kainuu, North Karelia and northeast Finland). According to observations made by utilities harmful hoar frost snow loads appear at heights of more than 200–250 m above the sea level.

In the winter 2006 there was an extremely wide and difficult snow load occurrence in a part of Lapland [9]. The fact that the soil was not frozen after warm and wet autumn made it even worse. The soil froze up slowly and the ground frost did not support the trees as normally and many whole trees were felled. This effect was pronounced in sandy soils.

In the coastal region and inland a snow load is often caused by originally wet or icy snowfall. Wet snow easily sticks to branches and gathers more even dry snow around.

This kind of snow loads rarely produce heavy loading on conductors. In accordance with the interruption statistics the case s*now and ice load* on conductor and on other structures have in Inland and Lapland caused equal number of faults. In the coastal region there are much fewer faults in the same case.

The case *tree fallen by snow load* causes failures mostly in inland and least in Lapland. The reason for the low fault amounts in Lapland is probably the type of the growing saw timber tree. It has to be noticed that the year 2006 is missing from the statistics and then crown snow-loads caused remarkable damage in eastern Lapland.

5. Climate change

5.1 Models used in climate change predictions

The results presented here are based on scenarios of changes in certain climate variables. The regional climate model, RCAO[1] consists of two main components dealing with the aerosphere model RCA and the Baltic Sea model RCO. The RCAO model is composed of $106 \times 102 = 10812$ horizontal grid squares, having an area of $49 \times 49\ \text{km}^2$. The grid covers the most part of Europe [1].

The data was obtained from the Finnish Meteorological Institute, VTT as well as from articles written by Räisänen et al. [11] and Ruokolainen [12]. In all cases two global climate models ECHAM4-OPYC3 and HadAM3-H were used to deliver boundary conditions for the RCAO model [1]. The magnitude of the climate change is often given as the global change of the average temperature. The uncertainty of the temperature change depends on the emission scenario selected for the calculation and on the other hand on the differences between the models. The uncertainty of the different models has been estimated in the article written by Ruokolainen [12]. Emission scenarios describe how greenhouse gas emissions evolve in the future. A2 and B2 emission scenarios drafted by IPCC were used in the calculations. The emission scenario A2 is based on a consumer society, in which the amount of greenhouse gases (carbon dioxide, methane and nitrous oxide) increases more than in the scenario B2. The emission scenario B2 aims at a sustainable development.

Results from six 30-year regional climate model runs have been adopted in the study. Two of these were control runs for the period 1961–1990 and four were the prediction runs for the period 2071–2100. The calculations are presented in detail in an article written by Räisänen [11]. In this research the target period is 2016–2045. As a consequence, it is assumed that the change of each climate variable from the control period 1961–1990 to the period 2016–2045 is linear. The change is assumed to be half of predicted value between the control period and 2071–2100. The climate predictions were determined for the following climate variables:

- precipitation
- temperature
- hoar frost
- thunder
- ground frost
- wind.

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[1] RCAO is the Rossby Centre regional Atmosphere-Ocean model, incorporating the Rossby Centre Regional Atmosphere Model, RCA, and the Rossby Centre Regional Ocean Model, RCO. The RCAO model domain is approximately Europe.

Four combinations of the climate models and scenarios were used in the calculated for the above mentioned climate variables:

Global climate model	Emission scenario
ECHAM4-OPYC3	A2
ECHAM4-OPYC3	B2
HadAM3-H	A2
HadAM3-H	B2

From these combinations only two predictions are presented: **the smallest and the biggest change predictions from the control period to the period 2016–2045** for all climate variables are presented in the previous chapter. The smallest change prediction is based on about 0,5 ºC increase in temperature and the biggest change prediction on about 1,5 ºC increase. The climate models cover the regions of the Baltic Sea area and practically the most part of Europe. The combination of the global climate model and the emission scenario used in the prediction calculations are mentioned above every picture. The RCAO-model was the main component in every prediction. Although the change predictions are presented quite accurately in the following, they show relatively reliably only the tendency of the changes of the climate variables. The results give the mean value of 30 years, not any particular year [1].

The changes of the climate variables are introduced in Figures 5-1 to 5-7 and Tables 5-1 to 5-5. The effects of the changes are presented in chapter 5.2. More accurate descriptions of the changes are introduced in report [1].

Precipitation:

The precipitation is defined as a quantity of water falling to the Earth at a specific place within a specified period of time. Figure 5-1 shows the changes of winter and summer average precipitations from the control period to the period 2016–2045. It should be noticed that the same percentage of change does not necessarily cause the same amount of changes in different places in Finland. The average precipitation will increase both in winter and in summer. In winter the increase will be bigger than in summer.

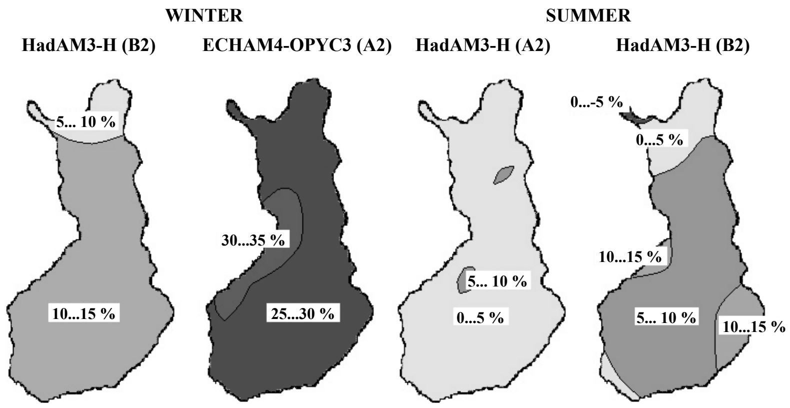


Figure 5-1. Changes in the winter and summer average precipitations from the control period to the period 2016–2045. Two predictions are presented; the left picture in each pair presents the smallest change and the right picture the biggest change [11].

Figure 5-2 shows the changes of snow and water maximum precipitations from the control period to the period 2016–2045. The maximum precipitation is the maximum quantity of precipitation in six hours.

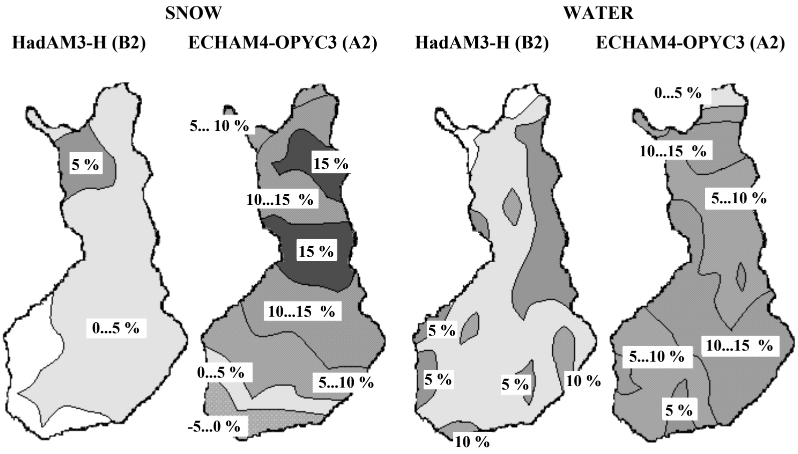


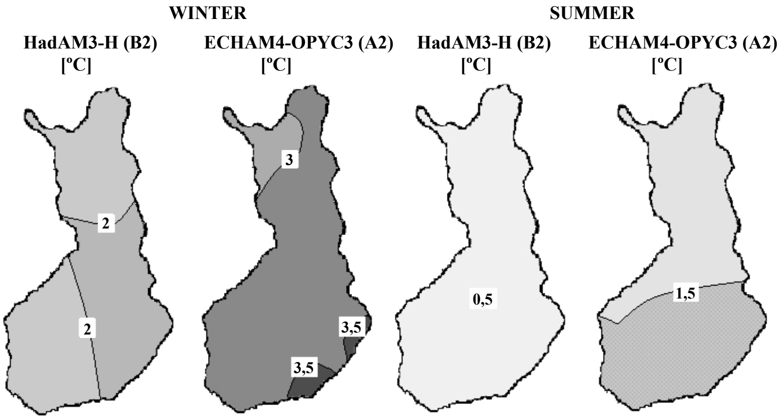
Figure 5-2. Changes in the snow and water maximum precipitations from the control period to the period 2016–2045. The left picture of the both picture pair presents the smallest change and the right picture the biggest change prediction [12].

The maximum snow and water precipitations will increase. In Finland the limits for a rainstorm are defined [8]:

2,5 mm	in 5 minutes
3,5 mm	in 10 minutes
4,5 mm	in 15 minutes
7,0 mm	in 1 hour
ca. 14 mm	in 12 hours
ca. 20 mm	in 24 hours.

Temperature:

Temperature has been defined at a height of two meters from ground level in degrees centigrade. Figure 5-3 shows changes of the average temperature from the control period to the period 2016–2045. The average temperature will rise and in winter it will increase more than in summer. Temperature of Lapland approaches the temperature of Middle Finland and temperature of Middle Finland approaches the temperature of southern Finland.



WINTER

SUMMER

HadAM3-H (B2) [°C]

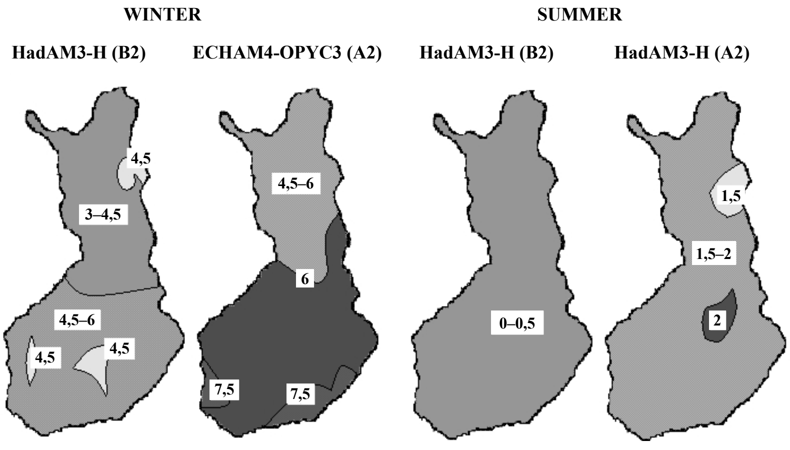
ECHAM4-OPYC3 (A2) [°C]

HadAM3-H (B2) [°C]

ECHAM4-OPYC3 (A2) [°C]

Figure 5-3. Changes in the winter and summer mean temperature from the control period to the period 2016–2045. The left picture of the both picture pairs presents the smallest change and the right picture the biggest change [11].

Figure 5-4 presents the changes of the extreme temperature from the control period to the period 2016–2045. The extreme temperature will rise. In winter the increase will be bigger than in summer.



WINTER

SUMMER

HadAM3-H (B2)

ECHAM4-OPYC3 (A2)

HadAM3-H (B2)

HadAM3-H (A2)

Figure 5-4. Changes in the extreme temperatures from the control period to the period 2016–2045. The left pictures (winter) show the smallest and the biggest change in minimum values as well as the right pictures (summer) show the changes in maximum values [12].

The extreme temperatures in Finland are defined those lying within the below mentioned limits from 100-year statistics:

98–100 %	exceptionally mild in winter or hot weather in summer
0–2 %	exceptionally cold in winter or cool in summer.

The highest temperature in Finland is 35,9 ºC, measured in Turku in 1914. The minimum value -51,5 ºC has been measured in Kittilä, Lapland in 1999 [8].

Hoar frost:

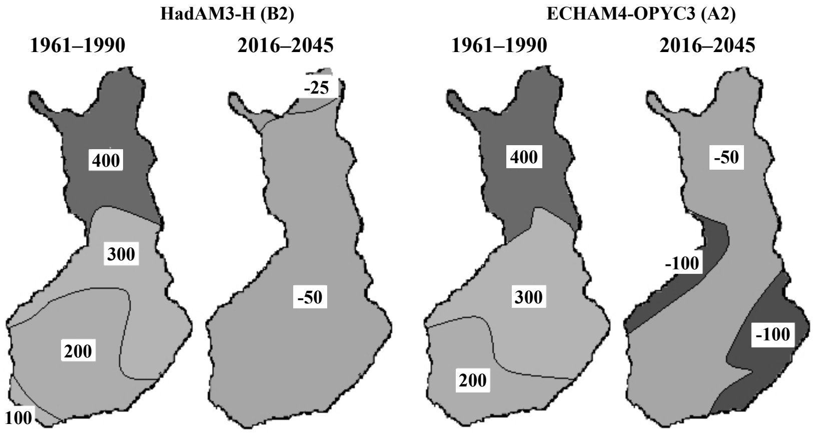


Figure 5-5. Changes in the hoar frost time [h] in January from the control period to the period 2016–2045. The left pair of pictures presents the smallest change prediction and the right pair of picture the biggest change prediction.

The hoar frost starts to form when the air temperature equals the dew point i.e. the relative humidity is 100 %. In these conditions small super cooled water droplets condensate and tend to attach on the cold surfaces. The time when the circumstances are suitable for hoar frost has been evaluated based on the predicted air temperature and relative humidity. Figure 5-5 shows the changes of the hoar frost time in January from the control period to the period 2016–2045.

The time when the circumstances are suitable for developing hoar frost will decrease. The figure 5-5 presents only the hoar frost time in January but the hoar frost time will decrease also in other months. The predictions indicate that the hoar frost time will decrease in all regions except the hill region of Vaara-Suomi (Kainuu, North Karelia and northeast Finland). In the hilled regions the amount of hoar frost is predicted to increase. Due to the climate change the temperature in the wintertime will rise and the Baltic Sea will remain widely open. Moisture will be formed above the unfrozen see and the mist will flow to inland along with southwest and west winds. The humid air mass when moving upwards will be frozen and easily sticks onto different surfaces.

Sometimes significant damage can be caused to trees because of frost formation and snow load on branches, see Figure 5-6. The formation of frost and snow clumps is significant starting from 200–300 metres above the sea level [10].

Figure 5-6. Crown snow loads in Posio, Lapland [10].

Thunder:

It is not possible to predict the occurrence of thunder using climate models because their resolution is too coarse. As a result, the thunder day prediction is based on two facts; temperature will rise in summer and increasing temperature means more thunders. However, it should be noticed that this evaluation is very coarse. Figure 5-7 presents the changes of thunder days from the control period to the period 2016–2045. The occurrence of thunder will increase. In southern Finland the number of thunder days will increase more than in northern Finland.

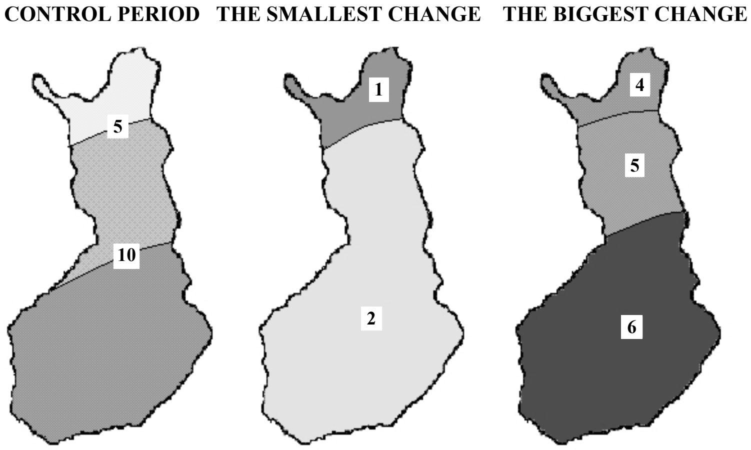


Figure 5-7. Changes in thunder days (number/year) between the control period and the smallest and biggest prediction presented for the period 2016–2045.

Ground frost:

Determination of ground frost is based on the frost sum. The frost sum is the sum of daily mean temperatures which are below zero degrees calculated from the beginning of the frost period. The unit of the frost sum is degree days [8]. The maximum frost sum in the Southern Finland is 500–1000 degree days and in the Northern Finland 1000–2000 degree days, these average values have been measured during 1974–1997. Ground frost begins to form when the frost sum exceeds 25 degree day. If there is no snow on the ground, the ground frost thickness can be estimated using frost sum of the winter. Normally the snow layer slows down the freezing of the ground. Figure 5-8 presents the changes of the frost sum in November from the control period to the period 2016–2045.

According to the climate model result, frost sum will decrease in autumn and in spring, meaning that the ground frost period shortens. In the Central and Southern Finland the ground is unfrozen in November and often also in December. In the Northern Finland ground is normally already frozen in December.

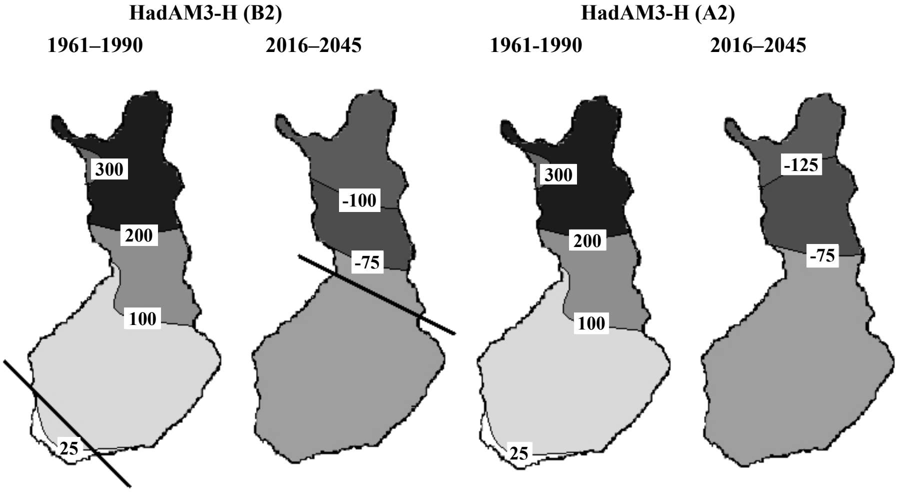


Figure 5-8. Changes in frost sum in November from the control period to the period 2016–2045. The left pair of maps presents the smallest change and the right pair the biggest change prediction. The black line shows the ground frost limit at the end of November. To the south of this line the ground is unfrozen.

If there is no snow on the ground the maximum thickness of the ground frost can be estimated to decrease from 100–150 cm to the value of 50–100 cm in the Southern and Central Finland until the end of this century. In the Northern Finland the decrease will be from 200–300 cm to 100–200 cm [8].

Wind:

Wind speed has been simulated for 30 years period as an average value of ten minutes at the height of ten meters. This research was focused at wind speeds that can cause damage to the electricity network. The limit speed has been defined as a value that is exceeded less than for one hour during the control period. In Finland the limit wind speed varies from 10,5 m/s to 12,5 m/s in different areas. Those kinds of winds can include squalls and in particular squalls cause damage to the electric network. Tables 5-1 and 5-2 show the changes of windiness from the control period to the period 2016–2045. Tables 5-1 and 5-2 present the biggest and the smallest values of the hour sum of each area.

The prediction of the wind speed is based on hour sum of area (hour/year/grid box). The hour sum of area is a good method to assess damages of wind. The wind conditions vary depending on the region. As a result of that Finland was divided into eight different areas. Figure 5-9 shows the grid boxes of RCA2 climate model and the division of area.

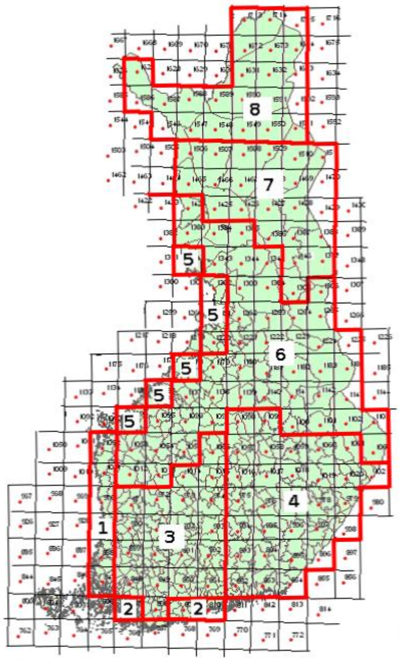


Figure 5-9. The grid boxes of RCA2 climate model and the division of area.

Table 5-1. The biggest values of the hour sum in grid box and the changes of values. Values are grid box-specific.

Area	1961–1990	2016–2045	Change [%]	Limit speed [m/s]	Simulation
1	0,60	1,14	89	12,5	ECHAM4-OPYC3 (B2)
2	0,33	0,63	91	12,5	ECHAM4-OPYC3 (B2)
3	0,39	0,84	115	10,5	ECHAM4-OPYC3 (B2)
4	0,34	0,49	44	10,5	ECHAM4-OPYC3 (B2)
5	0,26	0,82	213	11,5	ECHAM4-OPYC3 (B2)
6	0,14	0,30	114	10,5	ECHAM4-OPYC3 (B2)
7	0,26	0,45	71	10,5	ECHAM4-OPYC3 (A2)
8	0,25	0,41	62	12,5	ECHAM4-OPYC3 (B2)

Table 5-2. The smallest values of the hour sum of grid box and the changes of values. Values are grid box-specific.

Area	1961–1990	2016–2045	Change [%]	Limit speed [m/s]	Simulation
1	0,67	0,42	-37	12,5	HadAM3-H (A2)
2	0,13	0,10	-23	12,5	HadAM3-H (A2)
3	0,23	0,17	-26	10,5	HadAM3-H (B2)
4	0,11	0,09	-23	10,5	HadAM3-H (A2)
5	0,46	0,22	-53	11,5	HadAM3-H (A2)
6	0,06	0,00	-100	10,5	HadAM3-H (A2)
7	0,08	0,10	25	10,5	HadAM3-H (A2)
8	0,30	0,32	7	12,5	HadAM3-H (A2)

The occurrence of high wind speed when the ground is frozen and unfrozen is shown in Tables 5-3 to 5-5. The limit wind speed is 10,5 m/s and it is assumed that ground is frozen when the frost sum exceed 25 degree days. The frost sum is a cumulative sum for those average daily temperatures, which are below zero. The frost sum is given as an absolute value. The values for the control period and the period 2016–2045 are given.

Table 5-3. Values of occurrence of high wind speed in the control period when the ground is unfrozen or frozen. The wind's speed limit is 10,5 m/s and it is assumed that ground is frozen when the frost sum is more than 25 degree days.

Area	Unfrozen [h/a]	Frozen [h/a]	The relative time of unfrozen [%]
1	2,33	2,70	46
2	3,80	0,77	83
3	0,08	1,00	7
4	0,05	1,40	3
5	0,54	1,13	32
6	0,00	1,07	0
7	0,07	0,73	9
8	0,56	13,2	4

The results of Table 5-4 are based on ECHAM4-OPYC3 with emission scenario A2 and the results of Table 5-5 are based on the same global model with emission scenario B2. The areas in the following tables are shown in Figure 5-9.

Table 5-4. Values of occurrence of high wind speed in the period 2016–2045 when the ground is unfrozen or frozen. The wind's speed limit is 10,5 m/s and it is assumed that ground is frozen when the frost sum is more than 25 degree days. Results are based on ECHAM4-OPYC3 with emission scenario A2.

Area	Unfrozen [h/a]	Frozen [h/a]	The relative time of unfrozen [%]
1	9,62	1,80	84
2	7,94	0,35	95
3	0,41	0,62	40
4	0,16	0,82	16
5	1,94	1,30	60
6	0,08	1,09	6
7	0,05	1,47	3
8	0,67	21,3	3

Table 5-5. Values of occurrence of high wind speed in the period 2016–2045 when the ground is unfrozen or frozen. The wind's speed limit is 10,5 m/s and it is assumed that ground is frozen when the frost sum is more than 25 degree days. Results are based on ECHAM4-OPYC3 with emission scenario B2.

Area	Unfrozen [h/a]	Frozen [h/a]	The relative time of unfrozen [%]
1	7,62	2,79	73
2	7,00	0,74	90
3	0,56	0,82	40
4	0,23	1,15	16
5	1,37	1,62	46
6	0,08	1,54	6
7	0,04	0,58	6
8	0,56	21,0	3

According to the predictions the occurrence of high wind speeds when the ground is unfrozen increases in areas 1–6 and decreases in areas 7 and 8.

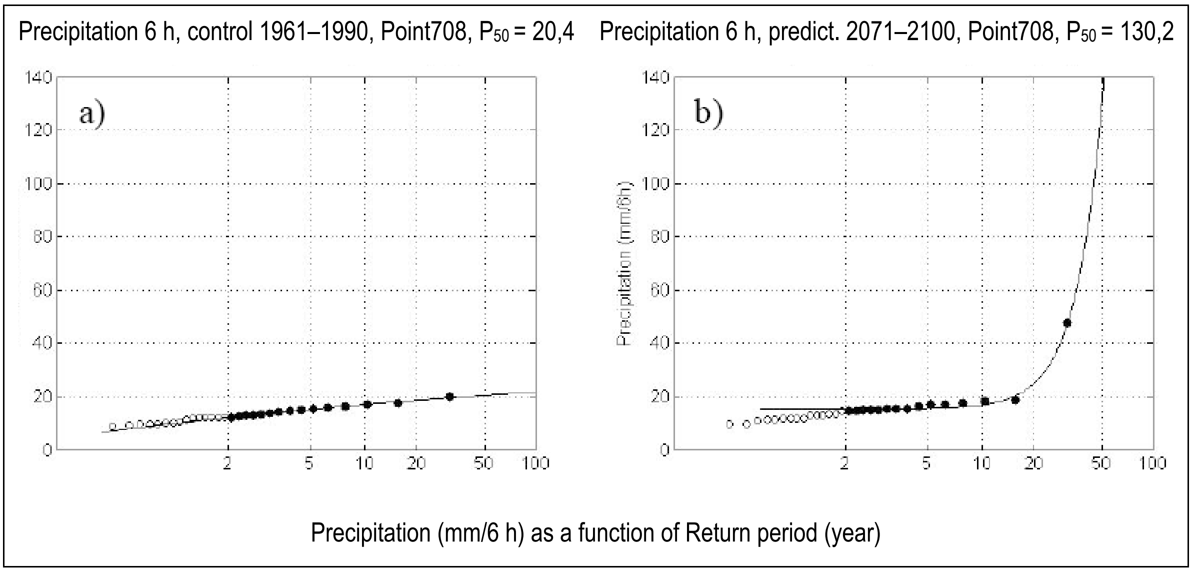
The results of the smallest and the biggest predictions are totally different. One model predicts that occurrence of high wind speed will increase and the other predicts that the occurrence of high wind speed will decrease. Although the results are different, it is expected that wind will cause more damage to the electricity network because ground frost period will get shorter and occurrence of thunder will increase. Ground frost can prevent trees from falling in the heavy winds and increasing occurrence of thunder means that there will be more heavy squalls.

Extreme weather events:

Changes in extreme weather events with climate change have been estimated for northern Europe by Rossby Centre coupled atmosphere – Baltic Sea regional climate model simulations [13]. Two driving global climate models and two forcing scenarios were used. The estimates were made by comparing, at each grid point, 50-year return values for the simulation periods of 1961–1990 and 2071–2100.

The most significant predicted changes in the study area are in the extremes of maximum and minimum air temperatures. The increase in the extreme surface wind speed is mostly small. The 50-year return value for the precipitation amount in five days is predicted to increase by over 50 % in many areas. The extreme snow water equivalent is predicted to decrease very significantly in most of the study area but increase in some highland areas. Very heavy snow fall will become generally more frequent. From the point of view of adapting structural design planning to climate change, the results suggest that the emphasis should be in the design practices in regard to flooding. The estimated changes in other structural design criteria are generally less significant or favourable.

Figure 5-10 is an example of the extreme events. It shows the extreme increase of precipitation in six hours.



Precipitation 6 h, control 1961–1990, Point708, P_{50} = 20,4

Precipitation 6 h, predict. 2071–2100, Point708, P_{50} = 130,2

Figure 5-10. Example of a probability plot for the annual extremes of the precipitation amount in six hours in the control run (a) and in the prediction for 2071–2100 (b). This example shows a rare case of a very exceptional largest value in the scenario run [13].

The occurrence of heavy snow falls is very important to the power line maintenance. The analysis suggests that, despite a widespread decrease in total annual snowfall in a warmer climate, extreme six hour snow precipitation will increase in most parts of the Nordic area. Increasing extreme snow precipitation intensities may initiate more severe snow and ice accretion on structures, such as power lines and communication towers [13].

5.2 Regional influence of climate change

Regional influences of the essential changes of weather conditions on planning and building the electric network are described in the following. The most remarkable influence on the changes in failure numbers has the following categories: *wind and storm, thunder, snow and ice load* as well as *tree fallen by snow load.* Additionally, other factors to be taken into account are temperature and precipitation in the planning phase and ground frost and snow cover in the building phase.

Wind and storm cause failures by felling trees and bending and blowing up branches on conductors. Ground frost and snow load have influence on the tree falls caused by wind forces so that unfrozen soil and snow load increase the windfalls. This category includes also the faults caused by wind and storm during the thunder storms. The number of faults is based on the predicted changes in wind (Tables 5-1 to 5-5), precipitation (Figure 5-2), ground frost (Figure 5-8) and temperature (Figure 5-3).

Thunder origin failures are caused by the lightning over voltages. The over voltages damage mainly conductors or transformers. The number of failures due to thunder are directly taken from the predicted changes in thunder days (number/year) shown in Figure 5-7.

Snow and ice load refers to snow and ice on the line or other structures. Usually the snow and ice layers start to grow on the lines due to hoar frost, so generating snow load and thus stressing the line mechanically by straining the conductors. The snow burden can create a strong tensile load on a corner pole, which can lead to falling or breaking of the pole. The conductors may be heavily sagged and they can touch undergrowth or in case of the common poles contact low-voltage conductors. The snow load can also damage the conductor but does not necessarily cause the fault immediately. Other structures failing due to the ice and snow load are pole-mounted uncovered disconnectors. Especially harmful event occurs when the temperature drops below zero after wet snowfall freezing the wet snow around the device. The values for failures are based on the changes occurring in the hoar frost (Figure 5-5), in snow and water precipitation (Figures 5-1 and 5-2) and in the average and extreme temperatures (Figures 5-3 and 5-4).

Tree fallen by snow load-case arises from the trees that have been bent or fallen due to snow and ice. In that case the tree typically falls during wet snowfall. Wet snow easily sticks to branches and gathers more snow around forming a heavy snow cover around the tree. The trees strained by the snow load are often flexible broad-leaved trees, but even tall trees can fall due to the snow burden. In *Tree fallen by snow load*-case the numbers of failures are based on the changes occurring in the hoar frost (Figure 5-5), in snow and water precipitation (Figures 5-1 and 5-2), in the average and extreme temperatures (Figures 5-3 and 5-4) and in the ground frost (Figure 5-8). Increasing hoar frost and precipitation increase the stress. Rising temperature increases the number of failures as long as the precipitation is ice or wet snow. Decreasing ground frost increases the number of the fallen trees, because in the no-frost case the trees fall more easily.

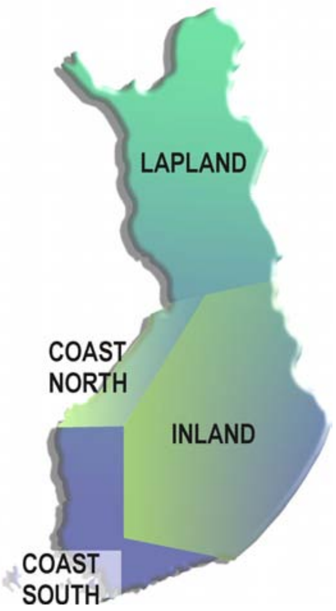


Figure 5-11. Division of area.

The regions used in the next study are shown in Figure 5-11. The division into regions is based on the predictions of the climate change and failure statistics. Influence of the changes in weather conditions is presented using two predictions. In the tables:

prediction 1 = the smallest change prediction
prediction 2 = the biggest change prediction.

In certain predictions the smallest change prediction would lead to even lower stresses than in the current case. However, it is reasonable to keep the present level in all building.

5.2.1 Coast, south

The southern coast means the coast of the Gulf of Finland and the Bothnian Sea see Figure 5-11.

Table 5-6. Relative values of the most remarkable reasons for failures in the southern coast.

Weather condition	**Prediction 1**	**Prediction 2**
Wind and storm	1,0	2,0
Thunder	1,2	1,5
Snow and ice load	1,0	1,3
Tree fallen by snow load	1,0	1,3

The studied region, southern coast, includes the wind areas 1 to 4 shown in Figure 5-9. Tables 5-3 to 5-5 give the values for the high wind speed occurrence. Areas 1 and 2 are partly on the sea. This is a remarkable reason for the fact that especially values in the grid boxes of area 1 are much higher than those in areas 2 to 4.

In the smallest change prediction the rate of change of the extremely high wind speeds are the following:

area 1	-37 %
area 2	-23 %
area 3	-26 %
area 4	-23 %.

When the changes in ground frost time (Figure 5-8), precipitation (Figures 5-1 and 5-2) and thunder days (Figure 5-7) are considered, the change in the wind stress does not follow the present knowledge of wind forecast. In the smallest change prediction the changes of ground frost, precipitation and thunder day compensate the decreasing of the extremely high wind speeds. Based on these facts the wind and storm values remain the same.

In the biggest changes prediction the rate of change of the wind speeds are the following:

area 1	+89 %
area 2	+91 %
area 3	+115 %
area 4	+44 %.

Area 4 ranges far into inland and this explains partly the difference compared to the other areas. The biggest change prediction is the worst case and thus the weighting factors are higher than in the smallest change prediction. One has also to take into account the changes in the precipitation, ground freezing and number of thunder days as well as their influence on the wind conditions. The change of the wind is 100 % in biggest change prediction. The failures caused by thunder increase 20 % in the smallest change prediction and 50 % in the biggest change prediction.

Ice and snow load: According to the forecasts the weather conditions suitable for hoar frost decrease in both predictions (Figure 5-5). In that case the predicted snow load stresses on the conductors are lower than the current one. A more problematic effect is icing of the disconnectors, in which both precipitation and temperature affect. In wintertime the precipitation increases about 10–15 % in the smallest change prediction and according to the maximum snowfall prediction for six hours there will be no change. Due to the rising temperature the increased precipitation turns mainly into rain. In the biggest change prediction the precipitation in winter increases 25–30 %. According to the forecasts the maximum snow precipitation lightly decreases or remains the same. This change in the biggest change prediction is regarded harmful, because this prediction considers the possibility in which the rainfall turns into wet snow, which again will freeze around the devices when temperature drops. Based on the previous, the stress in the smallest change prediction remains and in the biggest change prediction the stress increases 30 %.

Tree fallen by snow load: In the coast south of Vaasa the precipitation in winter increases according to the smallest change prediction about 10–15 % and no change is found in a maximum snowfall forecast. Due to rising temperature the increased precipitation turns mainly into rain. Based on these facts there is no change in the smallest change prediction. According to the biggest change prediction the precipitation in winter increases 25–30 %. The maximum snow precipitation lightly decreases or remains the same. In the biggest change prediction there is an increase of 30 %, because in this prediction the possibility in which the rainfall turns into very harmful wet snow is considered. When the ground is in early winter unfrozen, the ground frost does not support trees and they can fall more easily.

5.2.2 Coast, north

The northern coast means the coast of the Bothnian Bay, north of Vaasa, see Figure 5-11.

Table 5-7. Relative values of the most remarkable reasons for failures in the northern coast.

Weather condition	**Prediction 1**	**Prediction 2**
Wind and storm	1,0	2,5
Thunder	1,2	1,6
Snow and ice load	1,0	1,4
Tree fallen by snow load	1,1	1,4

The wind and storm-value is based on predicted wind speeds presented in Tables from 5-1 to 5-5. The studied area, coast of Bothnian Bay, includes the wind areas 5 and 6. In the smallest change predictions the rate of change of the extremely high wind speeds are the following:

• area 5	-53 %
• area 6	-100 %.

Even though the figures above show complete decreasing of the heavy winds in area 6 they will not come to an end. In prediction there will be no winds above the limit speed. Regarding the failures caused by the wind, also changes in the ground frost time (Figure 5-8), precipitation (Figures 5-1 and 5-2) and thunder days (Figure 5-7) are considered. Thus, the wind and storm values will remain the same i.e. the change is 0 %.

In the biggest change prediction the rates of the change of wind speeds are:

area 5	+213 %
area 6	+114 %.

The biggest change prediction is the worst prediction and thus the weighting coefficients have higher values. The changes in precipitation, ground frost and number of thunder days are also taken into account. Based on the previous the change in the biggest change prediction is 150 %. The failures caused by thunder increase 20 % in the smallest change prediction and 60 % in the biggest change prediction.

Snow and ice load: According to the predictions the weather conditions suitable for hoar frost decrease in both predictions (Figure 5-5). In the wintertime the precipitation increases about 10–15 % in the smallest change prediction, and the predicted maximum snowfall during six hours will change 0 to 5 %. Due to the rising temperature the increased precipitation turns mainly into rain. In the biggest change prediction the precipitation in winter increases 30–35 %. According to the forecasts the maximum snow precipitation increases 5–10 %. Based on these facts the stress in the smallest change prediction remains the same and in the biggest change prediction the stress increases 40 %.

Tree fallen by snow load: In the winter the precipitation increases about 10–15 % in the smallest change prediction and the predicted maximum snowfall will change 0 to 5 %. Based on the previous the change in the smallest change prediction is +10 %. In the biggest change prediction precipitation in winter increases 30–35 % and the maximum snow precipitation increases 5–15 %. Moreover, the unfrozen soil will not support the trees in early winter. Based on the change in precipitation the stress in the biggest change prediction will increase by 40 %.

5.2.3 Inland

Table 5-8. Relative values of the most remarkable reasons for failures in inland. There are two values in the cases of snow and ice load and tree fallen by snow load, where the value in parenthesis is the relative value in Vaara-Suomi (region at more than 250 m above the sea level).

Weather condition	**Prediction 1**	**Prediction 2**
Wind and storm	1,0	2,0
Thunder	1,2	1,6
Snow and ice load	1,0	1,3 (2,0)
Tree fallen by snow load	1,1	1,4 (2,0)

The wind and storm-value is based on the predicted wind speed values presented in Tables from 5-1 to 5-5. The areas 3, 4 and 6 belong to the inland.

In the smallest change prediction the rate of change of the extremely high wind speeds are the following:

area 3	-26 %
area 4	-23 %
area 6	-100 %.

In the failures caused by the wind the changes occurred in ground frost time (Figure 5-8), precipitation (Figures 5-1 and 5-2) and thunder days (Figure 5-7) are also considered. On this basis the wind and storm values will remain the same in the smallest change prediction.

In the biggest change prediction the rates of change of wind speeds are:

area 3	+115 %
area 4	+44 %
area 6	+114 %.

The biggest change prediction is the worst case and thus the weighting coefficients have higher values. The changes in the precipitation, ground frost and number of thunder days are also taken into account. Based on the previous the change in the biggest change prediction is +100 %. In the inland the thunderstorms increase 20 % in the smallest change prediction and 60 % in the biggest change prediction.

Snow and ice load: According to the predictions the weather conditions suitable for hoarfrost decrease in both predictions (Figure 5-5). In winter the precipitation increases about 10–15 % in the smallest change prediction, and the predicted maximum snowfall during six hours will change 0–5 %. In the biggest change prediction the precipitation in winter increases 25–30 %. According to the forecasts the maximum snow precipitation increases 5–10 %. Based on the previous the stress in the smallest change prediction remains the same and in the biggest change prediction the stress increases 30 %. Especially in the hill region of Vaara-Suomi i.e. in the eastern part of area 6 it is reasonable to prepare oneself for an increasing amount of hoar frost generated crown-snow loads. A present observation is that a forested area gathers more hoar frost and snow than an open terrain. The hoar frost generation is most harmful from the beginning of December to the middle of January. Few minus degrees and a weak and moist southwest or west wind form conditions most favourable for the hoar frost generation. The hoar frost is especially harmful at the height of more than 250 m above the sea level. The temperature in winter will increase along with the climate change and the Baltic Sea remains widely open. Moisture will be formed above the unfrozen see and the mist will flow to inland along with south and west winds. This kind of humid air mass when moving upwards will be frozen and easily sticks onto different surfaces and possibly causes remarkable damage. Table 5-8 has two values in Column *prediction 2*, higher of which represents the progress of fault numbers in the Vaara-Suomi region at more than 250 m above the sea level. This takes into account the freezing due to hoar frost.

In *tree fallen by snow load*-case the precipitation in winter increases about 10–15 % in the smallest change prediction and according to the “maximum snowfall” -prediction the change will be 0–5 %. Due to rising temperature the increased precipitation turns mainly into rain. Based on the previous the change in the smallest change prediction is +10 %.

In the biggest change prediction the inland precipitation in winter increases 25–30 %. The maximum predicted snow precipitation increases 5–15 % so that there is practically no change in the southern part and the change in northern part is 15 %. Moreover, the unfrozen soil will not support the trees in early winter. Based on the previous the stress in the biggest change prediction will increase 40 %. In Vaara-Suomi region large amounts of crown snow-loads may be generated due to hoar frost at the height more than 250 m above the sea level. Table 5-8 has two values in Column *prediction 2*. The higher value represents the change in failures in the Vaara-Suomi area.

5.2.4 Lapland

The wind and storm-value is based on the predicted wind speed values presented in Tables 5-1 to 5-5. Lapland is including the areas 6, 7 and 8 of Fig. 5-11. In the smallest change predictions the predicted rates of the change of wind speeds are:

area 6	-100 %
area 7	+25 %
area 8	+8 %.

Table 5-9. Relative values of the most remarkable reasons for failures in Lapland. There are two values in the case of snow and ice load, where the value in parenthesis refers to the relative value in Vaara-Suomi (region at more than 250 m above the sea level).

Weather condition	Prediction 1	Prediction 2
Wind and storm	1,1	1,8
Thunder	1,2	1,5
Snow and ice load	1,0	1,0 (2,0)
Tree fallen by snow load	1,1	1,3

In the failures caused by the wind also the changes occurring in the precipitation (Figures 5-1 and 5-2), ground frost (Figure 5-8) and thunder days (Figure 5-7) are also considered. The influence of precipitation and ground frost is not as high as in the other regions depending on the wood species (see Chapter 4). On this basis the wind and storm values will increase 10 % in the smallest change prediction.

In the biggest change prediction the rates of change are:

area 6	+114 %
area 7	+71 %
area 8	+62 %.

The changes in precipitation, ground frost and number of thunder days are also considered in the failures caused by wind. Based on this the “wind and storm” values will increase 70 % in the biggest change prediction. In Lapland thunderstorms will increase 20 % according to the smallest change prediction and about 50 % in the biggest change prediction.

Snow and ice load: According to the predictions the weather conditions suitable for hoar frost decrease in both predictions. In Lapland, in addition to the hill region of Vaara-

Suomi, it is reasonable to prepare oneself for an increasing amount of hoar frost generated snow loads. In winter the precipitation increases about 10–15 % in the smallest change prediction and the predicted maximum snowfall during six hours will increase 0–5 %. In the biggest change prediction the precipitation in winter increases 25–30 %. According to the forecasts the maximum snow precipitation increases 5–15 %. Based on the previous the stress in the smallest change prediction remains the same and in the biggest change prediction the stress increases 30 %. Table 5-9 has two values in Column *prediction 2*, the value in parenthesis represents the progress of fault number in hilly and mountain region at more than 250 m above the sea level.

Tree fallen by snow load: In Lapland the precipitation in winter increases about 10–15 % in the smallest change prediction and according to the predicted maximum snowfall the change will be 0–5 %. The change in the smallest change prediction is +10 %. Hoar frost has to be taken into account, but its influence is smaller than in Vaara-Suomi due to the stand of forest typical for Lapland. In accordance with the biggest change prediction in Lapland the precipitation in wintertime increases 25–30 %. The maximum predicted snow precipitation increases 10–15 %. The change in the biggest change prediction is +30 %.

5.3 Local influence of climate change

Besides the previously mentioned regional effects the climate chance has local impacts, too. The increase of precipitation and humidity may increase rotting damages in wooden structures. The worst cases have been observed in sandy soil. Particularly, the silt and clay grounds soften remarkably by increase of humidity and in that case the pole footings may decay. Also the local landslides are possible on the slopes.

Flooding of cities and rivers caused by potential heavy rains shall be taken into account when planning the placement for transformers and other structures unshielded from water. The flooding problems may increase if the rainwater outlets are under dimensioned or blocked up. The same is valid for coastal and island regions, where the possible sea-level rise is worth to consider in placing the structures.

In the certain terrain topologies for instance near hogbacks the weather conditions, like heavy rains, hails and thunderstorms, may significantly differ from that in the neighbourhood. These kind of difficult local areas are often known and the precautions are possible.

In conjunction with poles, stays and other supporting structures the stresses due to freezing and thawing soil have to be taken into account. Unfrozen ground does not usually cause problems, but freezing and thawing several times a year, can eventually lead to moving of the ground and thus decaying the structures. All previously mentioned conditions are local. Especially in the regions which already have observations, those conditions shall be dealt with during the field planning. [1]

6. Impact of climate change on costs and failure durations

This chapter represents the magnitude of the climate change effects as the yearly costs [€/a] and the failure durations [h/a]. The maintenance and other costs per unit as well as the interruption duration have been obtained from the unit price list of the electric network components [4], the questionnaire study performed in November 2006 as well as discussions with the steering group. The questionnaire was sent to all ten distribution companies participating in the project. The different line structures, different regions and different terrain types have been studied. The results have been calculated using two predictions called the *smallest change prediction* and the *biggest change prediction*.

The annual costs in the following tables have been calculated for a 10 km long line. On an average the utility has almost 1500 km/company medium voltage lines [2], the majority of which is bare overhead lines. In the following calculations it has been assumed that there are 150 of this kind of 10 km feeders, a half in the forest and the rest evenly in the field and on the roadside.

The studied structures are

- bare overhead line
- covered conductor lines (PAS, BLX)
- underground cable.

The terrain types under examination are:

- field
- forest
- roadside.

The regions are shown in Figure 5-11:

- southern coast
- northern coast
- inland
- Lapland.

Moreover, the changes in the hilled regions of inland and Lapland are presented. In the calculations the assumed service time is 40 years. The interest rate is 5 %. The length of the lines is 10 km. The equations used in the calculation are shown in Annex 1.

The costs which the climate change affects consist of maintenance costs caused by line clearing and trimming and outage costs including the reasons *wind and storm, thunder,* *snow and ice load* and *tree fallen by snow load*. Other costs consist of expenses due to investment, loss, inspection, service as well as outage costs caused by other weather conditions and other reasons. Other costs are shown in order to compare the additional costs of the climate change with total costs. The parameters used in the calculations starting from the costs affected by the climate change are presented in the following. In this context clearing means hacking of undergrowth and trimming is made using helicopters.

The line clearing and trimming are considered as maintenance costs. The present interval is six years in clearing and 16 years in trimming. In both climate change calculations the intervals are five and 12 years respectively. The interval for clearing will decrease because the rising temperature increases growing period. The clearing cost in forest is 150 €/km and the trimming cost 1200 €/km. The clearing of the ground below the line costs 150 €/km and the trimming is half from the costs in the forest, 600 €/km. The underground cable and overhead line on the field have no clearing or trimming costs.

The outage costs in the climate change study include the expenses for the fault repairing, interruption and duty to compensate for the outage duration. The fault repairing cost is in the overhead line network 1600 €/fault and for the underground cables 3200 €/fault. The maintenance and other costs are based on the answers of the questionnaire study performed in November 2006. The numbers of faults used in the *outage cost and failure duration*-calculations are regionally shown in Tables 6-1 to 6-3. The values have been derived from Tables 4-1 to 4-3.

Table 6-1. Number of failures in the present case in both northern and southern coast.

Northern and southern coast	**Bare overhead line [events/100 km]**			**Covered conductor line [events/100 km]**			**Underground cable [events/100 km]**
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**	**Independent on the terrain**
Wind and storm	0,00	2,25	1,13	0,00	1,13	0,56	0,00
Thunder	0,55	0,55	0,55	0,28	0,28	0,14	0,20
Snow and ice load	0,06	0,11	0,11	0,03	0,06	0,03	0,00
Tree fallen by snow load	0,00	0,49	0,25	0,00	0,25	0,12	0,00
Other weather conditions	0,13	0,13	0,13	0,07	0,07	0,07	0,10
Other reasons total	2,49	2,49	2,49	2,49	2,49	2,49	0,50

Table 6-2. Number of failures in the present case in inland.

Inland	**Bare overhead line [events/100 km]**			**Covered conductor line [events/100 km]**			**Underground cable [events/100 km]**
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**	**Independent on the terrain**
Wind and storm	0,00	3,29	1,65	0,00	1,65	0,82	0,00
Thunder	0,57	0,57	0,57	0,29	0,29	0,14	0,20
Snow and ice load	0,17	0,34	0,34	0,09	0,17	0,09	0,00
Tree fallen by snow load	0,00	0,91	0,46	0,00	0,46	0,23	0,00
Other weather conditions	0,08	0,08	0,08	0,04	0,04	0,04	0,10
Other reasons total	2,28	2,28	2,28	2,28	2,28	2,28	0,50

Table 6-3. Number of failures in the present case in Lapland.

Lapland	**Bare overhead line [events/100 km]**			**Covered conductor line [events/100 km]**			**Underground cable [events/100 km]**
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**	**Independent on the terrain**
Wind and storm	0,00	0,46	0,23	0,00	0,23	0,12	0,00
Thunder	0,39	0,39	0,39	0,20	0,20	0,10	0,20
Snow and ice load	0,12	0,24	0,24	0,06	0,12	0,06	0,00
Tree fallen by snow load	0,00	0,10	0,05	0,00	0,05	0,03	0,00
Other weather conditions	0,04	0,04	0,04	0,02	0,02	0,02	0,10
Other reasons total	1,39	1,39	1,39	1,39	1,39	1,39	0,50

The column *overhead line, forest* in Tables 6-1 to 6-3 refers to the average value of the failure statistics between 1998 and 2003. In the calculation of other parameters the following has been taken into account: Moving the line to the roadside decreases stress caused by *wind and storm* and *tree fallen by snow load* by 50 %. In the same way the use of the covered conductors decreases the stress due to climate by 50 %. In that case the use of the covered conductor and moving it to the roadside decrease the number of failures due to *wind and storm* and *tree fallen by snow load* by 75 % as compared to the case of a *bare overhead line* in *forest*. The above mentioned assumptions have been made because no reliable statistics exists. The statistics of 2005 gives for the covered conductor lines a fault frequency of 0,14 faults/100 km [6]. The corresponding number for the overhead lines is 2,29. In *other reasons total*-row the number of faults is of the same order, even though the animals do not cause a fault as easily as in bare overhead lines.

In the calculations the climate change has been taken into account in the failures due to *wind and storm, thunder, snow and ice load* and *tree fallen by snow load*. The number of the failures in these two prediction calculations has been obtained for each area by multiplying the present number of faults by a regional factor given in Tables 5-6 to 5-9.

The outage costs and failure durations have been calculated using *customer's interruption duration per one fault* presented in Table 6-4. *Bare overhead line* in *forest* and *ground cable* is a rounded value from an average of the failure statistics 1998–2003. The fault repairing time of the *field*- and *roadside*-cases is assumed to be a half of that in forest. Repairing a covered conductor line is supposed to take 20 % more time than repairing a bare conductor line. The yearly interruption duration has been calculated multiplying the interruption duration of one fault by the number of faults.

Table 6-4. Customer's interruption duration per one fault [h/fault] according to the conductor type and terrain.

	Field	**Forest**	**Roadside**
Bare overhead line	0,5	1,0	0,5
Covered conductor	0,6	1,2	0,6
Ground cable	1,0		

The number of the high speed and delayed automatic reclosings is presented in Table 6-5 for the bare overhead lines and in Table 6-6 for the covered conductor lines. Underground cable network is not protected using a high speed or delayed automatic reclosing. Starting point in the study is that in the *bare overhead line*-case the number of high speed automatic reclosings per 100 km [events/100 km] is 50 in *forest*, 40 in *roadside* and 30 in *field.* The number of the delayed automatic reclosings is respectively 15 in *forest*, 10 in *roadside* and 7 in *field.* The failure reasons for the high speed and delayed automatic reclosings (AR) are divided into following groups: *wind and storm* 20 %, *thunder* 30 %, *snow and ice load* 15 %, *other weather conditions* 5 % and *other reasons totally* 30 % [7].

Table 6-5. Numbers of high speed AR and delayed AR [events/100 km] in a bare overhead line network.

	Bare overhead line					
	Field		**Forest**		**Roadside**	
	High speed AR	**Delayed AR**	**High speed AR**	**Delayed AR**	**High speed AR**	**Delayed AR**
Wind and storm	6,0	1,4	10	3,0	8,0	2,0
Thunder	9,0	2,1	15	4,5	12	3,0
Snow and ice load	2,3	0,5	3,8	1,1	3,0	0,8
Tree fallen by snow load	2,3	0,5	3,8	1,1	3,0	0,8
Other weather conditions	1,5	0,4	2,5	0,8	2,0	0,5
Other reasons total	9,0	2,1	15	4,5	12	3,0

Table 6-6. Numbers of high speed AR and delayed AR [events/100 km] in a covered conductor network.

	Covered conductor					
	Field		**Forest**		**Roadside**	
	High speed AR	**Delayed AR**	**High speed AR**	**Delayed AR**	**High speed AR**	**Delayed AR**
Wind and storm	2,0	0,4	2,0	0,4	2,0	0,4
Thunder	3,0	0,6	3,0	0,6	3,0	0,6
Snow and ice load	0,8	0,2	0,8	0,2	0,8	0,2
Tree fallen by snow load	0,8	0,2	0,8	0,2	0,8	0,2
Other weather conditions	0,5	0,1	0,5	0,1	0,5	0,1
Other reasons total	3,0	0,6	3,0	0,6	3,0	0,6

The power consumption data used in the *outage cost*-calculation is presented in Table 6-7. The results are classified into the following groups: fault interruption, high speed automatic reclosing and delayed automatic reclosing. The electric power corresponds to the typical consumption of a rural feeder. The average electric power is 104 kW. In order to simplify the calculation an evenly distributed consumption has been assumed.

Table 6-7. Consumption and proportion of total consumption.

	Household	**Agriculture**	**Industry**	**Public**	**Service**
Energy consumption [kWh/a]	500 000	200 000	70 000	70 000	70 000
Proportion of total consumption [%]	55 %	22 %	7,7 %	7,7 %	7,7 %

Table 6-8 shows the unit costs of a fault interruption.

Table 6-8. Unit costs for fault interruptions [14].

Consumer	**Fault interruption**		**High speed AR**	**Delayed AR**
	€/kW	**€/kWh**	**€/kW**	**€/kW**
Household	0,36	4,29	0,11	0,48
Agriculture	0,45	9,38	0,20	0,62
Industry	3,52	24,5	2,19	2,87
Public	1,89	15,1	1,49	2,34
Service	2,65	29,9	1,31	2,44

The basis for the fixed compensation amount is that significant compensations are usually caused by the heavy storms or extremely difficult crown snow-load conditions. These kinds of weather conditions occur seldom on a single feeder. The assumption in the calculation is that in the present situation there will be one, in the smallest change prediction two and in the biggest change prediction three weather conditions leading to fixed compensation. Additionally, in the fixed compensation calculations have been made the following assumptions:

- the load is evenly distributed
- 10 % of customers on the feeder suffer from an outage of 12–24 hours
- 5 % of customers on the feeder suffer from an outage of 24–72 hours
- 1 % of customers on the feeder suffer from an outage of 72–120 hours
- over 120 hours outages do not exist
- at present a weather condition leading to the fixed compensation occurs 10 years after the line has been constructed
- in the smallest change prediction a severe weather condition leading to the fixed compensation occurs 10 and 20 years after the line construction

- in the biggest change prediction a severe weather condition leading to the fixed compensation occurs 10, 20 and 30 years after the line construction
- on an overhead line in the field and underground cable the faults leading to the fixed compensation do not occur.

Table 6-9 shows the distribution tariffs.

Table 6-9. Average distribution price (cnt/kWh) for consumer types. [3]

	Average distribution price incl. tax [cnt/kWh]				
	Household	**Agriculture**	**Industry**	**Public**	**Service**
Distribution price	3,97	4,22	2,71	3,13	3,13

The distribution price for household consumers is the mean value of tariffs K2, L1 and L2 (K1 is not included, because no block of flats exists in rural areas), for agriculture the mean value of M1 and M2, for industry the mean value of T1, T2, T3 and T4 as well as for public service the mean of T1 and T2, see *symbols and abbreviations*.

In the investment costs used in the calculation the price of the bare conductor line is 20 k€/km, the covered conductor line 26 k€/km and the underground cable 46 k€/km. The unit costs of the investments and the maintenance were checked in November 2006.

The calculations of the loss costs include only the main transformer and the medium voltage line, because the other loss components remain unchanged. The costs have been calculated supposing 1,4 % losses of the total consumption of the line and the distribution price 4 cnt/kWh.

The inspection costs include the checking of poles in case of rot as well as the maintenance inspection and characteristic data collection. For the underground cables these costs include general inspection. The unit price for rot inspection is 115 €/km and the inspection interval is 12 years. The corresponding values for the maintenance inspection and data collection are 110 €/km with six year interval and for the cable inspection 100 €/km with six year interval as well. The service costs have been calculated with unit prices of 400 €/km for the bare overhead line, 300 €/km for the covered conductor line and 250 €/km for the underground cable. The service interval is six years.

The number of failures caused by other weather conditions and other reasons is presented in Tables 6-1 to 6-3. The fault and outage costs have been calculated in the same way as in the climate change-case.

6.1 Regionally studied costs

In the following the changes of the annual costs are presented regionally. Regional division is shown in Figure 5-11. The calculation results are given for each region in a table form. The following information is divided into totally eight tables per region.

Bare overhead lines:

- annual costs of those bare overhead line cost components, which the climate change affects
- annual costs of those bare overhead line cost components, which the climate change does not affect
- changes of the present costs of the line caused by the climate change compared to the combined total costs.

Covered conductor lines: three tables similar to the above mentioned.
Ground cable:

- annual costs of the ground cable cost components, which the climate change affects
- annual costs of the ground cable cost components, which the climate change does not affect.

The percentage changes of the underground cable compared to the overall costs are less than 0,2 %.

6.1.1 Coast, south

Table 6-10. Annual costs [€/a] of those bare overhead line cost components, which the climate change affects.

Coast, south	Annual costs of bare overhead line [€/a]								
	Present situation			Prediction 1			Prediction 2		
	Field	Forest	Road-side	Field	Forest	Road-side	Field	Forest	Road-side
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	97	540	330	110	560	340	140	980	570
Interruption costs	36	380	120	43	390	130	54	680	210
High speed AR	99	170	130	110	180	140	160	270	210
Delayed AR	47	100	67	51	110	73	75	160	110
Std. compensation	0	34	34	0	55	55	0	68	68
Total	280	1 900	1 100	320	2 300	1 400	430	3 100	1 800

Table 6-11. Annual costs [€/a] of those bare overhead line cost components, which the climate change does not affect.

Coast, south	Annual costs of bare overhead line [€/a]		
	Field	Forest	Roadside
Investment	11 660	11 660	11 660
Losses	470	470	470
Inspections + maintenance	790	790	790
Repair	420	420	420
Interruption costs	110	160	110
High speed AR	50	90	70
Delayed AR	30	50	40
Total	13 530	13 640	13 650

Table 6-12. Changes of the present costs of bare overhead line caused by climate change compared to combined total costs.

Coast, south	Bare overhead line					
	Prediction 1			Prediction 2		
	Field	Forest	Roadside	Field	Forest	Roadside
Clearing and trimming	0,0 %	1,9 %	1,2 %	0,0 %	1,9 %	1,2 %
Repair	0,1 %	0,1 %	0,1 %	0,4 %	2,8 %	1,6 %
Interruption costs	0,0 %	0,1 %	0,0 %	0,1 %	1,9 %	0,6 %
High speed AR	0,1 %	0,1 %	0,1 %	0,4 %	0,6 %	0,5 %
Delayed AR	0,0 %	0,1 %	0,0 %	0,2 %	0,4 %	0,3 %
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,3 %	2,4 %	1,6 %	1,1 %	7,9 %	4,5 %

Table 6-13. Annual costs [€/a] of covered conductor cost components, which the climate change affects.

Coast, south	**Annual costs of Covered conductor [€/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	53	270	160	62	280	170	77	490	280
Interruption costs	23	220	72	27	230	75	34	400	130
High speed AR	33	33	33	36	36	36	53	53	53
Delayed AR	13	13	13	15	15	15	21	21	21
Std. compensation	0	34	34	0	55	55	0	68	68
Total	120	1 260	760	140	1 600	980	190	2 020	1 170

Table 6-14. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Coast, south	**Annual costs of Covered conductor [€/a]**		
	Field	**Forest**	**Roadside**
Investment	15 150	15 150	15 150
Losses	470	470	470
Inspections + maintenance	650	650	650
Repair	410	410	410
Interruption costs	130	180	130
High speed AR	18	18	18
Delayed AR	7	7	7
Total	16 840	16 890	16 840

Table 6-15. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation.

Coast, south	**Covered conductor**					
	Prediction 1			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0,0 %	1,7 %	1,0 %	0,0 %	1,7 %	1,0 %
Repair	0,1 %	0,0 %	0,0 %	0,1 %	1,2 %	0,7 %
Interruption costs	0,0 %	0,0 %	0,0 %	0,1 %	1,0 %	0,3 %
High speed AR	0,0 %	0,0 %	0,0 %	0,1 %	0,1 %	0,1 %
Delayed AR	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,1 %	1,9 %	1,2 %	0,4 %	4,1 %	2,3 %

Table 6-16. Annual costs of ground cable cost components, which the climate change affects.

Coast, south	**Ground cable**		
	Present situation	**Prediction 1**	**Prediction 2**
Repair	64	77	96
Interruption costs	22	27	33
Total	86	103	129

Table 6-17. Annual costs [€/a] of ground cable cost components, which the climate change does not affect.

Coast, south	**Ground cable**
Investment	26 800
Losses	470
Inspections + maintenance	500
Repair	190
Interruption costs	70
Total	28 000

6.1.2 Coast, north

Table 6-18. Annual costs [€/a] of bare overhead line cost components, which the climate change affects.

Coast, north	Annual costs of bare overhead line [€/a]								
	Present situation			Prediction 1			Prediction 2		
	Field	Forest	Road-side	Field	Forest	Road-side	Field	Forest	Road-side
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	97	540	330	110	570	350	150	1 180	670
Interruption costs	36	380	120	40	390	130	60	810	250
High speed AR	99	170	130	110	180	150	180	300	240
Delayed AR	47	100	70	50	110	70	90	180	120
Std. compensation	0	30	30	0	60	60	0	70	70
Total	280	1 900	1 100	310	2 300	1 400	480	3 500	2 000

Table 6-19. Annual costs [€/a] of bare overhead line cost components, which the climate change does not affect.

Coast, north	Annual costs of bare overhead line [€/a]		
	Field	Forest	Roadside
Investment	11 660	11 660	11 660
Losses	470	470	470
Inspections + maintenance	790	790	790
Repair	420	420	420
Interruption costs	110	160	110
High speed AR	50	90	70
Delayed AR	30	50	40
Total	13 530	13 640	13 560

Table 6-20. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation.

Coast, north	Bare overhead line					
	Prediction 1			Prediction 2		
	Field	Forest	Roadside	Field	Forest	Roadside
Clearing and trimming	0,0 %	1,9 %	1,2 %	0,0 %	1,9 %	1,2 %
Repair	0,1 %	0,2 %	0,1 %	0,4 %	4,0 %	2,3 %
Interruption costs	0,0 %	0,1 %	0,1 %	0,2 %	2,8 %	0,9 %
High speed AR	0,1 %	0,1 %	0,1 %	0,6 %	0,9 %	0,7 %
Delayed AR	0,0 %	0,1 %	0,0 %	0,3 %	0,5 %	0,4 %
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,3 %	2,5 %	1,7 %	1,5 %	10,4 %	5,8 %

Table 6-21. Annual costs [€/a] of covered conductor cost components, which the climate change affects.

Coast, north	Annual costs of Covered conductor [€/a]								
	Present situation			Prediction 1			Prediction 2		
	Field	Forest	Road-side	Field	Forest	Road-side	Field	Forest	Road-side
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	48	270	140	57	290	140	77	590	290
Interruption costs	21	220	60	25	230	63	34	480	130
High speed AR	33	33	33	36	36	36	60	60	60
Delayed AR	13	13	13	15	15	15	24	24	24
Std. compensation	0	34	34	0	55	55	0	68	68
Total	120	1 300	730	130	1 600	930	200	2 200	1 200

Table 6-22. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Coast, north	Annual costs of Covered conductor [€/a]		
	Field	Forest	Roadside
Investment	15 150	15 150	15 150
Losses	470	470	470
Inspections + maintenance	650	650	650
Repair	410	410	410
Interruption costs	130	180	130
High speed AR	18	18	18
Delayed AR	7	7	7
Total	16 840	16 890	16 840

Table 6-23. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation

Coast, north	Covered conductor					
	Prediction 1			Prediction 2		
	Field	Forest	Roadside	Field	Forest	Roadside
Clearing and trimming	0,0 %	1,7 %	1,0 %	0,0 %	1,7 %	1,0 %
Repair	0,1 %	0,1 %	0,1 %	0,2 %	1,7 %	1,0 %
Interruption costs	0,0 %	0,1 %	0,0 %	0,1 %	1,4 %	0,4 %
High speed AR	0,0 %	0,0 %	0,0 %	0,2 %	0,1 %	0,2 %
Delayed AR	0,0 %	0,0 %	0,0 %	0,1 %	0,1 %	0,1 %
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,1 %	1,9 %	1,2 %	0,5 %	5,2 %	2,8 %

Table 6-24. Annual costs [€/a] of ground cable cost components, which the climate change affects.

Coast, north	**Ground cable**		
	Present situation	**Prediction 1**	**Prediction 2**
Repair	64	77	102
Interruption costs	22	27	35
Total	86	103	138

Table 6-25. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Coast, north	**Ground cable**
Investment	26 800
Losses	470
Inspections + maintenance	500
Repair	190
Interruption costs	70
Total	28 000

6.1.3 Inland

Table 6-26. Annual costs [€/a] of bare overhead line cost components, which the climate change affects. The values in parenthesis refer to those obtained in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	Annual costs of bare overhead line [€/a]								
	Present situation			Prediction 1			Prediction 2		
	Field	Forest	Road-side	Field	Forest	Road-side	Field	Forest	Road-side
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	120	820	480	140	850	510	180 (200)	1 470 (1 600)	850 (930)
Interruption costs	45	570	180	51	590	190	68 (75)	1 020 (1 110)	320 (350)
High speed AR	99	170	130	110	180	150	170 (180)	270 (300)	220 (240)
Delayed AR	47	100	67	52	110	74	78 (85)	170 (180)	110 (120)
Std. compensation	0	34	34	0	55	55	0	68	68
Total	310	2 400	1 300	350	2 800	1 600	500 (540)	4 000 (4 200)	2 200 (2300)

Table 6-27. Annual costs [€/a] of bare overhead line cost components, which the climate change does not affect.

	Annual costs of bare overhead line [€/a]		
	Field	Forest	Roadside
Investment	11 660	11 660	11 660
Losses	470	470	470
Inspections + maintenance	790	790	790
Repair	380	380	380
Interruption costs	96	150	96
High speed AR	53	89	71
Delayed AR	25	54	36
Total	13 470	13 590	13 500

Table 6-28. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation. The values in parenthesis refer to those in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	**Bare overhead line**					
	Prediction 1			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0,0 %	1,9 %	1,2 %	0,0 %	1,9 %	1,2 %
Repair	0,1 %	0,2 %	0,2 %	0,5 % (0,8 %)	4,1 % (4,9 %)	2,4 % (3,0 %)
Interruption costs	0,0 %	0,1 %	0,1 %	0,2 % (0,3 %)	2,9 % (3,4 %)	0,9 % (1,1 %)
High speed AR	0,1 %	0,1 %	0,1 %	0,5 % (0,6 %)	0,7 % (0,8 %)	0,6 % (0,7 %)
Delayed AR	0,0 %	0,1 %	0,0 %	0,2 % (0,3 %)	0,4 % (0,5 %)	0,3 % (0,4 %)
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,3 %	2,6 %	1,7 %	1,4 % (1,9 %)	10,2 % (11,8 %)	5,7 % (6,6 %)

Table 6-29. Annual costs [€/a] of covered conductor cost components, which the climate change affects. The values in parenthesis refer to those obtained in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	**Annual costs of covered conductor [€/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	59	410	200	68	430	210	90 (100)	740 (800)	370 (400)
Interruption costs	26	340	90	30	350	93	40 (44)	600 (660)	160 (180)
High speed AR	33	33	33	36	36	36	55 (60)	55 (60)	55 (60)
Delayed AR	13	13	13	15	15	15	22 (24)	22 (24)	22 (24)
Std. compensation	0	34	34	0	55	55	0	68	68
Total	130	1 500	820	150	1 900	1 000	210 (230)	2 500 (2600)	1 300 (1400)

Table 6-30. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Inland	**Annual costs of covered conductor [€/a]**		
	Field	**Forest**	**Roadside**
Investment	15 150	15 150	15 150
Losses	470	470	470
Inspections + maintenance	650	650	650
Repair	370	370	370
Interruption costs	120	170	120
High speed AR	18	18	18
Delayed AR	7	7	7
Total	16 790	16 840	16 790

Table 6-31. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation. The values in parenthesis refer to those in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	**Covered conductor**					
	Prediction 1			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0,0 %	1,6 %	1,0 %	0,0 %	1,6 %	1,0 %
Repair	0,1 %	0,1 %	0,1 %	0,2 % (0,3 %)	1,8 % (2,1 %)	1,0 % (1,3 %)
Interruption costs	0,0 %	0,1 %	0,0 %	0,1 % (0,1 %)	1,5 % (1,7 %)	0,5 % (0,6 %)
High speed AR	0,0 %	0,0 %	0,0 %	0,1 % (0,2 %)	0,1 % (0,1 %)	0,1 % (0,2 %)
Delayed AR	0,0 %	0,0 %	0,0 %	0,1 % (0,1 %)	0,0 % (0,1 %)	0,1 % (0,1 %)
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,1 %	1,9 %	1,2 %	0,5 % (0,7 %)	5,2 % (5,9 %)	2,8 % (3,2 %)

Table 6-32. Annual costs [€/a] of ground cable cost components, which the climate change affects.

Inland	Ground cable		
	Present situation	**Prediction 1**	**Prediction 2**
Repair	64	77	102
Interruption costs	22	27	35
Total	86	103	138

Table 6-33. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Inland	Ground cable
Investment	26 800
Losses	470
Inspections + maintenance	500
Repair	190
Interruption costs	67
Total	28 000

6.1.4 Lapland

Table 6-34. Annual costs [€/a] of bare overhead line cost components, which the climate change affects. The values in parenthesis refer to those obtained in Lapland at more than 250 m above the sea level.

Lapland	**Annual costs of bare overhead line [€/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	82	190	150	94	210	160	110 (130)	290 (320)	210 (250)
Interruption costs	31	130	55	35	150	61	42 (50)	198 (220)	78 (93)
High speed AR	99	170	130	110	190	150	150 (160)	250 (270)	200 (210)
Delayed AR	47	100	67	53	110	76	71 (76)	150 (160)	100 (110)
Std. compensation	0	34	34	0	55	55	0	68	68
Total	260	1 300	890	290	1 700	1 100	370 (420)	1 900 (2000)	1 280 (1350)

Table 6-35. Annual costs [€/a] of bare overhead line cost components, which the climate change does not affect.

Lapland	**Annual costs of bare overhead line [€/a]**		
	Field	**Forest**	**Roadside**
Investment	11 660	11 660	11 660
Losses	470	470	470
Inspections + maintenance	790	790	790
Repair	230	230	230
Interruption costs	58	88	58
High speed AR	53	89	71
Delayed AR	25	54	36
Total	13 290	13 380	13 320

Table 6-36. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation. The values in parenthesis refer to those in Vaara-Suomi (region at more than 250 m above the sea level).

Lapland	**Bare overhead line**					
	Prediction 1			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0,0 %	2,1 %	1,2 %	0,0 %	2,1 %	1,2 %
Repair	0,1 %	0,1 %	0,1 %	0,2 % (0,5 %)	0,6 % (0,9 %)	0,4 % (0,7 %)
Interruption costs	0,0 %	0,1 %	0,0 %	0,1 % (0,2 %)	0,4 % (0,6 %)	0,2 % (0,3 %)
High speed AR	0,1 %	0,2 %	0,1 %	0,4 % (0,5 %)	0,6 % (0,7 %)	0,5 % (0,6 %)
Delayed AR	0,0 %	0,1 %	0,1 %	0,2 % (0,2 %)	0,3 % (0,4 %)	0,2 % (0,3 %)
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,3 %	2,7 %	1,7 %	0,9 % (1,4 %)	4,3 % (4,9 %)	2,8 % (3,3 %)

Table 6-37. Annual costs [€/a] of covered conductor cost components, which the climate change affects. The values in parenthesis refer to those obtained in Lapland at more than 250 m above the sea level.

Lapland	**Covered conductor**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0	680	450	0	990	620	0	990	620
Repair	50	95	73	57	110	81	66 (85)	140 (160)	100 (124)
Interruption costs	22	78	32	25	87	36	29 (38)	120 (130)	46 (54)
High speed AR	33	33	33	37	37	37	50 (54)	50 (54)	50 (54)
Delayed AR	13	13	13	15	15	15	20 (22)	20 (22)	20 (22)
Std. compensation	0	34	34	0	55	55	0	68	68
Total	120	940	630	130	1 290	850	170 (200)	1390 (1420)	900 (940)

Table 6-38. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Lapland	Covered conductor		
	Field	**Forest**	**Roadside**
Investment	15 150	15 150	15 150
Losses	470	470	470
Inspections + maintenance	650	650	650
Repair	230	230	230
Interruption costs	71	100	71
High speed AR	18	18	18
Delayed AR	7	7	7
Total	16 600	16 630	16 600

Table 6-39. Changes of the covered conductor costs caused by climate change compared to the combined total costs of the present situation. The values in parenthesis refer to those in Vaara-Suomi (region at more than 250 m above the sea level).

Lapland	Covered conductor					
	Prediction 1			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Clearing and trimming	0,0 %	1,7 %	1,0 %	0,0 %	1,7 %	1,0 %
Repair	0,0 %	0,1 %	0,0 %	0,1 % (0,2 %)	0,3 % (0,4 %)	0,2 % (0,3 %)
Interruption costs	0,0 %	0,0 %	0,0 %	0,0 % (0,1 %)	0,2 % (0,3 %)	0,1 % (0,1 %)
High speed AR	0,0 %	0,0 %	0,0 %	0,1 % (0,1 %)	0,1 % (0,1 %)	0,1 % (0,1 %)
Delayed AR	0,0 %	0,0 %	0,0 %	0,0 % (0,1 %)	0,0 % (0,0 %)	0,0 % (0,0 %)
Std. compensation	0,0 %	0,1 %	0,1 %	0,0 %	0,2 %	0,2 %
Total	0,1 %	2,0 %	1,2 %	0,3 % (0,5 %)	2,5 % (2,8 %)	1,6 % (1,8 %)

Table 6-40. Annual costs [€/a] of ground cable cost components, which the climate change affects.

Lapland	**Ground cable**		
	Present situation	**Prediction 1**	**Prediction 2**
Repair	64	77	96
Interruption costs	22	27	33
Total	86	103	129

Table 6-41. Annual costs [€/a] of covered conductor cost components, which the climate change does not affect.

Lapland	**Ground cable [€/a]**
Investment	26 800
Losses	470
Inspections + maintenance	500
Repair	190
Interruption costs	67
Total	28 000

6.2 Regionally studied failure durations

In the following the changes of the failure durations are presented regionally for the bare overhead lines, covered conductor lines and underground cables in different geography. Regional division is shown in Figure 5-11.

6.2.1 Coast, south

Table 6-42. Annual failure durations [h/a] of bare overhead line. Length of line is 10 km.

Coast, south	**Annual failure durations of bare overhead line [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,23	0,06	0,00	0,23	0,06	0,00	0,45	0,11
Thunder	0,03	0,06	0,03	0,03	0,07	0,03	0,04	0,08	0,04
Snow and ice load	0,00	0,01	0,01	0,00	0,01	0,01	0,00	0,01	0,01
Tree fallen by snow load	0,00	0,05	0,01	0,00	0,05	0,01	0,00	0,06	0,02
Other weather conditions	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Other reasons total	0,07	0,12	0,07	0,07	0,12	0,07	0,07	0,12	0,07
Total	0,11	0,48	0,18	0,12	0,49	0,19	0,13	0,75	0,26

Table 6-43. Annual failure durations [h/a] of covered conductor. Length of line is 10 km.

Coast, south	**Annual failure durations of covered conductor [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,14	0,03	0,00	0,14	0,03	0,00	0,27	0,07
Thunder	0,02	0,03	0,01	0,02	0,04	0,01	0,02	0,05	0,01
Snow and ice load	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Tree fallen by snow load	0,00	0,03	0,01	0,00	0,03	0,01	0,00	0,04	0,01
Other weather conditions	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Other reasons total	0,10	0,15	0,10	0,10	0,15	0,10	0,10	0,15	0,10
Total	0,12	0,36	0,15	0,12	0,37	0,16	0,13	0,52	0,20

Table 6-44. Annual failure durations [h/a] of ground cable. Length of line is 10 km.

Coast, south	**Annual failure durations of ground cable [h/a]**		
	Present situation	**Prediction 1**	**Prediction 2**
Wind and storm	0,00	0,00	0,00
Thunder	0,02	0,02	0,03
Snow and ice load	0,00	0,00	0,00
Tree fallen by snow load	0,00	0,00	0,00
Other weather conditions	0,01	0,01	0,01
Other reasons total	0,05	0,05	0,05
Total	0,08	0,08	0,09

6.2.2 Coast, north

Table 6-45. Annual failure durations [h/a] of bare overhead line. Length of line is 10 km.

Coast, north	**Annual failure durations of bare overhead line [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,23	0,06	0,00	0,23	0,06	0,00	0,56	0,14
Thunder	0,03	0,06	0,03	0,03	0,07	0,03	0,04	0,09	0,04
Snow and ice load	0,00	0,01	0,01	0,00	0,01	0,01	0,00	0,02	0,01
Tree fallen by snow load	0,00	0,05	0,01	0,00	0,05	0,01	0,00	0,07	0,02
Other weather conditions	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Other reasons total	0,07	0,12	0,07	0,07	0,12	0,07	0,07	0,12	0,07
Total	0,11	0,48	0,18	0,12	0,49	0,19	0,13	0,87	0,29

Table 6-46. Annual failure durations [h/a] of covered conductor. Length of line is 10 km.

Coast, north	**Annual failure durations of covered conductor [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Wind and storm	0,00	0,14	0,03	0,00	0,14	0,03	0,00	0,34	0,08
Thunder	0,02	0,03	0,01	0,02	0,04	0,01	0,03	0,05	0,01
Snow and ice load	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Tree fallen by snow load	0,00	0,03	0,01	0,00	0,03	0,01	0,00	0,04	0,01
Other weather conditions	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Other reasons total	0,10	0,15	0,10	0,10	0,15	0,10	0,10	0,15	0,10
Total	0,12	0,36	0,15	0,12	0,37	0,16	0,13	0,60	0,21

Table 6-47. Annual failure durations [h/a] of ground cable. Length of line is 10 km.

Coast, north	**Annual failure durations of ground cable [h/a]**		
	Present situation	**Prediction 1**	**Prediction 2**
Wind and storm	0,00	0,00	0,00
Thunder	0,02	0,02	0,03
Snow and ice load	0,00	0,00	0,00
Tree fallen by snow load	0,00	0,00	0,00
Other weather conditions	0,01	0,01	0,01
Other reasons total	0,05	0,05	0,05
Total	0,08	0,08	0,09

6.2.3 Inland

Table 6-48. Annual failure durations [h/a] of bare overhead line. Length of line is 10 km. The values in parenthesis refer to those obtained in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	**Annual failure durations of bare overhead line [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,33	0,08	0,00	0,33	0,08	0,00	0,66	0,16
Thunder	0,03	0,06	0,03	0,03	0,07	0,03	0,05	0,09	0,05
Snow and ice load	0,01	0,03	0,02	0,01	0,03	0,02	0,01 (0,02)	0,04 (0,07)	0,02 (0,03)
Tree fallen by snow load	0,00	0,09	0,02	0,00	0,10	0,03	0,00	0,13 (0,18)	0,03 (0,05)
Other weather conditions	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Other reasons total	0,07	0,11	0,07	0,07	0,11	0,07	0,07	0,11	0,07
Total	0,11	0,63	0,22	0,12	0,65	0,23	0,13 (0,14)	1,04 (1,12)	0,34 (0,36)

Table 6-49. Annual failure durations [h/a] of covered conductor. Length of line is 10 km. The values in parenthesis refer to those obtained in Vaara-Suomi (region at more than 250 m above the sea level).

Inland	**Annual failure durations of covered conductor [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,20	0,05	0,00	0,20	0,05	0,00	0,39	0,10
Thunder	0,02	0,03	0,01	0,02	0,04	0,01	0,03	0,05	0,01
Snow and ice load	0,01	0,02	0,01	0,01	0,02	0,01	0,01	0,03 (0,04)	0,01
Tree fallen by snow load	0,00	0,05	0,01	0,00	0,06	0,02	0,00	0,08 (0,11)	0,02 (0,03)
Other weather conditions	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Other reasons total	0,09	0,14	0,09	0,09	0,14	0,09	0,09	0,14	0,09
Total	0,12	0,45	0,17	0,12	0,46	0,17	0,13	0,69 (0,74)	0,23 (0,24)

Table 6-50. Annual failure durations [h/a] of ground cable. Length of line is 10 km.

Inland	**Annual failure durations of ground cable [h/a]**		
	Present situation	**Prediction 1**	**Prediction 2**
Wind and storm	0,00	0,00	0,00
Thunder	0,02	0,02	0,03
Snow and ice load	0,00	0,00	0,00
Tree fallen by snow load	0,00	0,00	0,00
Other weather conditions	0,01	0,01	0,01
Other reasons total	0,05	0,05	0,05
Total	0,08	0,08	0,09

6.2.4 Lapland

Table 6-51. Annual failure durations [h/a] of bare overhead line. Length of line is 10 km. The values in parenthesis refer to those obtained in Lapland at more than 250 m above the sea level.

Lapland	**Annual failure durations of bare overhead line [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Wind and storm	0,00	0,05	0,01	0,00	0,05	0,01	0,00	0,08	0,02
Thunder	0,02	0,04	0,02	0,02	0,05	0,02	0,03	0,06	0,03
Snow and ice load	0,01	0,02	0,01	0,01	0,02	0,01	0,01	0,02 (0,05)	0,01 (0,02)
Tree fallen by snow load	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Other weather conditions	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Other reasons total	0,04	0,07	0,04	0,04	0,07	0,04	0,04	0,07	0,04
Total	0,07	0,19	0,09	0,07	0,21	0,09	0,08	0,25 (0,28)	0,11 (0,12)

Table 6-52. Annual failure durations [h/a] of covered conductor. Length of line is 10 km. The values in parenthesis refer to those obtained in Lapland at more than 250 m above the sea level.

Lapland	**Annual failure durations of covered conductor [h/a]**								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**	**Field**	**Forest**	**Roadside**
Wind and storm	0,00	0,03	0,01	0,00	0,03	0,01	0,00	0,05	0,01
Thunder	0,01	0,02	0,01	0,01	0,03	0,01	0,02	0,04	0,01
Snow and ice load	0,00	0,01	0,00	0,00	0,01	0,00	0,00 (0,01)	0,01 (0,03)	0,00 (0,01)
Tree fallen by snow load	0,00	0,01	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Other weather conditions	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Other reasons total	0,06	0,08	0,06	0,06	0,08	0,06	0,06	0,08	0,06
Total	0,07	0,16	0,07	0,07	0,17	0,08	0,08	0,19 (0,21)	0,08 (0,09)

Table 6-53. Annual failure durations [h/a] of ground cable. Length of line is 10 km.

Lapland	**Annual failure durations of ground cable [h/a]**		
	Present situation	**Prediction 1**	**Prediction 2**
Wind and storm	0,00	0,00	0,00
Thunder	0,02	0,02	0,03
Snow and ice load	0,00	0,00	0,00
Tree fallen by snow load	0,00	0,00	0,00
Other weather conditions	0,01	0,01	0,01
Other reasons total	0,05	0,05	0,05
Total	0,08	0,08	0,09

6.3 Summary of calculations

A summary of calculations is shown in the following. While reviewing the results one has to take into account that the chosen parameters have a significant effect on the calculation results.

The grand totals of yearly costs are shown in Table 6-54 for the bare overhead lines and in Table 6-55 for the covered conductor lines.

Table 6-54. The grand total of annual costs of the bare overhead lines. The values in parenthesis refer to those obtained in hill areas at more than 250 m above the sea level.

	Annual costs of bare overhead lines [k€/a]								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Roadside**
Coast, south	13,8	15,6	14,7	13,8	15,9	14,9	14,0	16,8	15,3
Coast, north	13,8	15,6	14,7	13,8	15,9	14,9	14,0	17,2	15,5
Inland	13,8	16,0	14,8	13,8	16,4	15,1	14,0 (14,0)	17,6 (17,8)	15,7 (15,8)
Lapland	13,5	14,7	14,2	13,6	15,1	14,4	13,7 (13,7)	15,3 (15,4)	14,6 (14,7)

Table 6-55. The grand total of annual costs of the covered conductor lines. The values in parenthesis refer to those obtained in hill areas at more than 250 m above the sea level.

	Annual costs of covered conductor lines [k€/a]								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Coast, south	17,0	18,2	17,6	17,0	18,5	17,8	17,0	18,9	18,0
Coast, north	17,0	18,2	17,6	17,0	18,5	17,8	17,0	19,1	18,0
Inland	16,9	18,3	17,6	16,9	18,7	17,8	17,0 (17,0)	19,3 (19,4)	18,1 (18,1)
Lapland	16,7	17,6	17,2	16,7	17,9	17,4	16,7 (16,8)	18,0 (18,1)	17,5 (17,5)

The overall costs of underground cable are about 28 k€/a in Finland regardless of a region. According to the prediction calculations the climate change has no influence on these costs.

Based on the calculations the impact of climate change is lowest in the overhead lines in the fields and highest in the overhead lines passing through the forest. The changes in the fault reparation and outage costs in the biggest change prediction are remarkably high. However, those costs are finally reasonably low, when compared to the overall costs. Even though the climate change factors have significant differences between those two predictions, the differences in the overall costs are not as remarkable.

Considering the biggest change prediction the highest overall costs and biggest changes occur in the hilled region of inland. According to the calculations the total costs of a bare overhead line passing through the forest increase about 12 % due to the climate change. The corresponding change for the line in the field is about 2 % and on the roadside about 7 %. On the other hand the total costs of a covered conductor line passing through the forest increase about 6 %, in the field about 1 % and on the roadside about 3 %. The failure reparation and outage costs are the most remarkable cost factors caused by the climate change for both line types. In the biggest change prediction the smallest change of costs is in Lapland. The total costs of a bare overhead line passing through the forest increase about 4 %, in the field about 1 % and on the roadside about 3 %. The corresponding values of a covered conductor line in the forest are about 3 %, in the field less than 1 % and on the roadside about 1 %.

In the smallest change prediction the total costs in the entire Finland increase for both bare overhead lines and covered conductor lines passing through the forest about 2 %, in the field less than 1 % and on the roadside about 2 %.

In the underground cable network the failure reparation and outage costs increase 50 % and 20 % according to the smallest and biggest predictions respectively. The change of the overall costs is especially low in both predictions in whole Finland. The change seen in the total costs of the urban networks is even smaller due to the expensive construction of cable networks.

The calculations with the real expenses included the clearing, repairing the fault and the fixed compensation. The results showed that the climate change increases yearly costs by an average of 35 k€/company in the *smallest change prediction* and of 55 k€/company in the *biggest change prediction*. If these results are proportioned to the calculated depreciation of the line investments the additional climate change costs represent 3 % and 5 % respectively.

Table 6-56 shows the total failure durations for a bare overhead line and Table 6-57 for a covered conductor line. Length of the line is 10 km. According to the calculations the failure durations of the underground cables do not practically change.

Table 6-56. Total failure durations for a bare overhead line [h/a]. Length of the line is 10 km. The values in parenthesis refer to those obtained in hill areas at more than 250 m above the sea level.

	Annual failure durations for bare overhead line [h/a]								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Coast, south	0,11	0,48	0,18	0,12	0,49	0,19	0,13	0,75	0,26
Coast, north	0,11	0,48	0,18	0,12	0,49	0,19	0,13	0,87	0,29
Inland	0,11	0,63	0,22	0,12	0,65	0,23	0,13 (0,14)	1,04 (1,12)	0,34 (0,36)
Lapland	0,07	0,19	0,09	0,07	0,21	0,09	0,08	0,25 (0,28)	0,11 (0,12)

Table 6-57. Total failure durations for a covered conductor line [h/a]. Length of the line is 10 km. The values in parenthesis refer to those obtained in hill areas at more than 250 m above the sea level.

	Annual failure durations for covered conductor line [h/a]								
	Present situation			**Prediction 1**			**Prediction 2**		
	Field	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**	**Field**	**Forest**	**Road-side**
Coast, south	0,12	0,36	0,15	0,12	0,37	0,16	0,13	0,52	0,20
Coast, north	0,12	0,36	0,15	0,12	0,37	0,16	0,13	0,60	0,21
Inland	0,12	0,45	0,17	0,12	0,46	0,17	0,13	0,69 (0,74)	0,23 (0,24)
Lapland	0,07	0,16	0,07	0,07	0,17	0,08	0,08	0,19 (0,21)	0,08 (0,09)

Studying the failure durations the results from the two predictions have significant differences. The changes of the failure durations between the present situation and the *smallest change prediction* are small, whereas in the *biggest change prediction* the changes are remarkable compared to the present day failure durations. For instance the failure durations of the line in the forest increase up to 80 % and on the roadside almost as much. In the fields there are practically no differences due to the climate change.

A proposal for next surveillance period 2008−2011 is that fixed compensations will be added to the controlled operative expenses (OPEX) in measuring the utility-specific efficiency. The outage costs in the efficiency measurements are proposed to be taken into account as investment variables together with OPEX costs and straight-line depreciations.

7. Effect of climate change on the most important distribution network components

7.1 Effect of climate change on current rating of underground cables

Helsinki University of Technology has estimated the effects of climate change on underground cables in this project. In this report the medium voltage cables have the main stress. The primary goal is to investigate the possible extreme circumstances due to the climate change. The results of that study are presented in detail in a separate report [Annex C, TKK report 1].

The ampacity (maximum allowable current) calculations have here been made using an algorithm based on an analytical set of thermal equations. The software Mathcad® was used to run the algorithm. The 20 kV, 3 cored cable of type AHXAMK-W was used in the study. The cable ratings are based on the manufacturer's data sheet given for the conductor temperature of 65 ºC and 90 ºC. The thermal resistivity 1,0 km/W has been used in determining the nominal current rating for different cross sections and conductor temperatures of the cables. The cable was buried at a depth of 0,7 meters in two ways; direct burial and tube installation. Certain environmental conditions were investigated in the study to demonstrate their effects on the cable current rating. Table 7-1 shows a brief description of the environmental conditions in terms of its ambient temperature, the thermal resistivity of a soil, ρ_s and the thermal resistivity of the dry soil, ρ_{dry}.

Table 7-1. Environmental conditions and parameters [Annex C, TKK report 1].

Environmental condition	**Ambient temperature[°C]**	**ρ_s [Km/W]**	**ρ_{dry} [Km/W]**
No moisture migration (moist environment)	20	1,2	-
Moisture migration in controlled environment (back fill)	20	1,2	2,5
Moisture migration in uncontrolled environment (native soil)	20	1,2	5
Fully dry environment (worst case)	20	5	-

In the controlled environment, the cable is installed in backfill (usually sand or crushed stone) with known properties, whereas in the uncontrolled case, the installation is in native soil, which in the worst case may be fully dried out due to a long-term dry period and the effects of the vegetation.

The following Tables 7-2 to 7-9 illustrate the calculated current ratings for different installations. The results are given in per unit (P.U.) values. Tables 7-2 to 7-5 show values of the direct burial installations. Table 7-2 can be regarded as a reference table for the calculated values in the direct burial installations. Tables 7-6 to 7-9 show the values for the tube installations. The rated current for a given temperature is taken from the data sheet.

The corresponding manufacturer's information is given in a slightly different way. For instance the thermal resistivity of a soil varies from 0,7 km/W to 3,0 km/W and the respective correction factors vary from 1,10 km/W to 0,63 km/W. Moreover the soil temperature from -5 ºC to +30 ºC has been taken into account [15]. According to the questionnaire study performed in November 2006 all utilities participating this project use the values 15 ºC for the soil temperature and 1 km/W for the thermal resistivity of a soil in the calculation of the cable loading capacity. The same values are used for both direct burial installation and ploughing the underground cables.

Table 7-2. Effect of no moisture migration and moisture migration on the current rating. Direct burial installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Direct burial without moisture migration, $\rho_s = 1{,}2$ km/W**	
	P.U current rating at	
	65 ºC	**90 ºC**
70	0,85	0,87
95	0,87	0,87
120	0,87	0,86
150	0,86	0,84
185	0,89	0,83
240	0,88	0,80
300	0,87	0,80

Table 7-3. Effect of moisture migration on the current rating in a controlled environment. Direct burial installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Direct burial with moisture migration in controlled environment, from ρ_s = 1,2 km/W to 2,5 km/W**	
	P.U current rating at	
	65 ºC	**90 ºC**
70	0,77	0,74
95	0,78	0,74
120	0,78	0,72
150	0,77	0,70
185	0,79	0,67
240	0,78	0,66
300	0,77	0,67

Table 7-4. Effect of moisture migration on the current rating in an uncontrolled environment. Direct burial installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Direct burial with moisture migration in uncontrolled environment, from ρ_s = 1,2 km/W to 2,5 km/W**	
	P.U current rating at	
	65 ºC	**90 ºC**
70	0,71	0,65
95	0,72	0,65
120	0,72	0,63
150	0,71	0,62
185	0,73	0,60
240	0,72	0,59
300	0,71	0,59

Table 7-5. Effect of moisture migration on the current rating in a fully dry environment. Direct burial installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Direct burial with or without moisture migration in the worst environment ρ_s = 5 km/W**	
	P.U current rating at	
	65 °C	**90 °C**
70	0,46	0,47
95	0,46	0,47
120	0,47	0,46
150	0,46	0,44
185	0,47	0,44
240	0,46	0,42
300	0,46	0,42

Figure 7-1 summarises the direct burial results shown in Tables 7-2 to 7-5 at the conductor temperature of 90 °C.

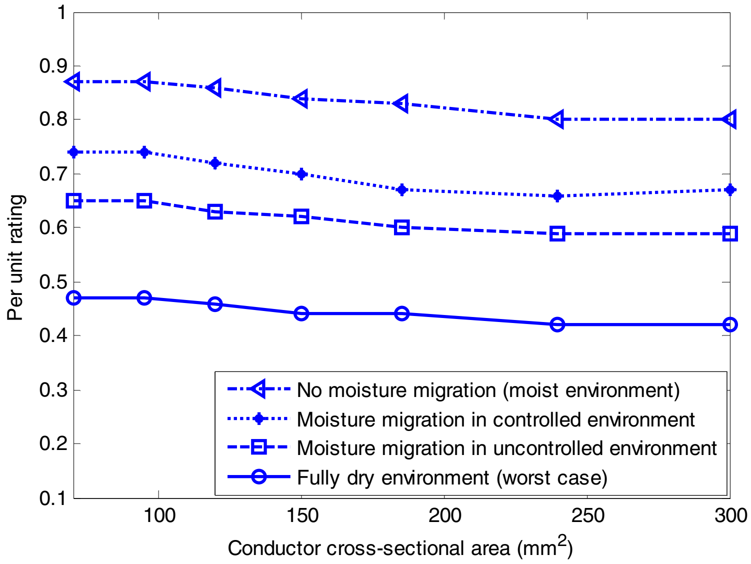


Figure 7-1. Cable installation in a depth of 0,7 meters, direct burial installation, four environmental conditions, conductor temperature 90 °C [Annex C, TKK report 1].

Table 7-6. Effect of moisture migration on the current rating in a controlled environment. Tube installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Tube installation without moisture migration ρ_s = 1,2 km/W**	
	P.U current rating at	
	65 °C	**90 °C**
70	0,74	0,77
95	0,76	0,77
120	0,76	0,76
150	0,75	0,74
185	0,77	0,73
240	0,76	0,70
300	0,76	0,71

Table 7-7. Effect of moisture migration on the current rating in a controlled environment. Tube installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Tube installation with moisture migration in controlled environment, from ρ_s = 1,2 km/W to 2,5 km/W**	
	P.U current rating at	
	65 °C	**90 °C**
70	0,75	0,73
95	0,76	0,72
120	0,76	0,70
150	0,75	0,69
185	0,77	0,68
240	0,76	0,65
300	0,75	0,66

Table 7-8. Effect of moisture migration on the current rating in an uncontrolled environment. Tube installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Tube installation with moisture migration in uncontrolled environment, from $\rho_s = 1{,}2$ km/W to 2,5 km/W**	
	P.U current rating at	
	65 ºC	**90 ºC**
70	0,75	0,67
95	0,76	0,68
120	0,76	0,66
150	0,75	0,65
185	0,76	0,63
240	0,74	0,60
300	0,74	0,60

Table 7-9. Effect of moisture migration on the current rating in a fully dry environment. Tube installation [Annex C, TKK report 1].

Cross Sectional area [mm^2]	**Tube installation without - with moisture migration, the worst environment $\rho_s = 5$ km/W**	
	P.U current rating at	
	65 ºC	**90 ºC**
70	0,48–0,49	0,50
95	0,49	0,49–0,50
120	0,49	0,48
150	0,48	0,47–0,48
185	0,47–0,50	0,46
240	0,48–0,47	0,43
300	0,47–0,48	0,44–0,45

An analytical formulation for the calculation of current rating/thermal capacity under various environmental conditions has been presented. The results are to a large extent confirmed by comparing with those obtained from FEMLAB. (Here FEM means the Finite Element Method which have the capability to solve many cases with very complex geometrical configuration.) As the moisture content decreases due to the moisture migration phenomenon occurring in the vicinity of a cable, the "allowed" current rating of the conductor also decreases for the same permissible thermal limits. Hence, it is suggested to load the cables at lower current ratings than those given in the specifications for safe and reliable operation. The current rating decreases due to moisture migration. The effect of decreasing current rating is more significant in the case of a direct burial than in a tube installation [Annex C, TKK report 1].

Slightly higher current ratings are obtained in the case of tube installation for a typical Finnish uncontrolled dry environment. However, it must be noticed that these ratings are substantially lower than the catalogue values. The pattern of decreasing current rating due to moisture migration under various environmental conditions is the same for minimum or maximum conductor cross-sectional area, which proves the applicability of this technique for any size of conductor.

In the worst case (fully dried out peaty native soil); the load capacity of the cables is reduced to less than 50 % of the nominal rating. These kind of conditions are possible during a long-term dry period (like in summer 2006), especially if there is vegetation close to the cable route.

The similar examination has been done for loading of low voltage underground cables in different soil conditions [Annex C, TKK report 2]. For the low voltage cables the dry soil conditions are even more important as their loading rate is often much higher than the loading rate of the medium voltage cables.

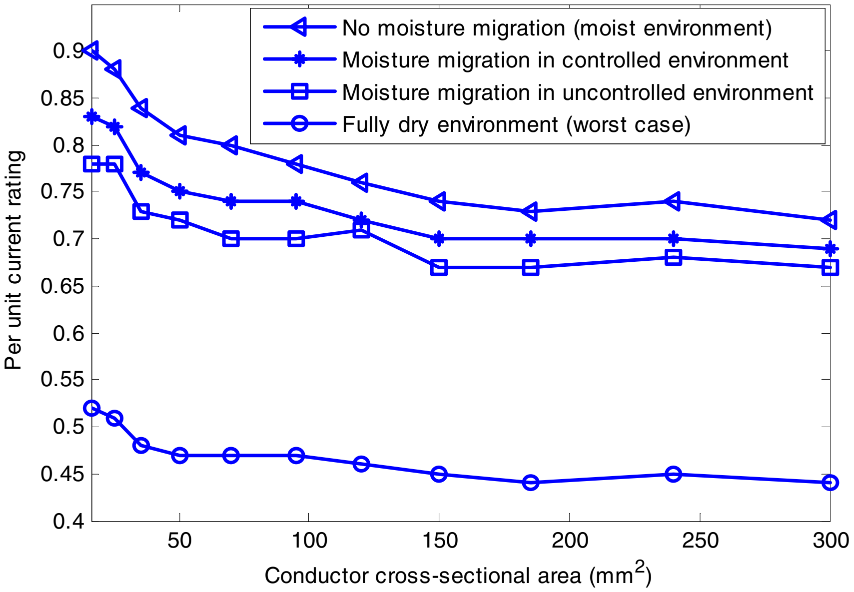


Figure 7-2. Low voltage cable installation. Per unit current ratings for direct burial under various environmental conditions, conductor at 70 °C [Annex C, TKK report 2].

7.2 Effect of climate change on transformers

Helsinki University of Technology also estimated the effects of climate change on the distribution and power transformers in this project. The primary goal is to investigate the possible extreme circumstances due to the climate change, in this case long summer hot weather periods. The transformers will be de-rated under such circumstances for the safe operation of these components. The results of that study are presented in detail in the TKK report 3, Annex C.

The factors affecting the life expectancy of a transformer have been studied in the report. The hot spot temperature and the load rate have been calculated at different ambient temperature values. The calculation gives the basis for either overloading the transformers at low ambient temperatures or de-rating at high ambient temperature values. Examples of the results are shown in Tables 7-10 and 7-11. The parameters used in the calculations are given in the report [Annex C, TKK report 3].

The loading capacity of the transformers shall be considered case-by-case. The transformer losses, the extreme temperature and its duration, dates and duration of the maximum load vs. the extreme circumstances as well as the time constants of the transformer have an influence on the final result.

Table 7-10. Hot spot temperature calculations at extreme temperature 33,8 °C for distribution transformers [Annex C, TKK report 3].

Rating (kVA)	Voltage level (kV/kV)	Mode of cooling	No load losses (W)	Load losses at rated current (W)	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H (for $K = 1$)	K (for $\theta_H = 98$ °C)
50	20/0,4	ONAN	150	1403	9,3	60,4	21,3	115,5	0,868
100	20/0,4	ONAN	245	1973	8,0	60,3	21,3	115,5	0,867
200	20/0,4	ONAN	465	2743	5,9	60,2	21,3	115,4	0,864
315	20/0,4	ONAN	680	3672	5,4	60,2	21,3	115,4	0,862
500	20/0,4	ONAN	930	5276	5,7	60,2	21,3	115,4	0,863
800	20/0,4	ONAN	1400	6859	4,9	60,2	21,3	115,3	0,861
1000	20/0,4	ONAN	1500	8864	5,9	60,2	21,3	115,4	0,864

Table 7-11. Hot spot temperature calculations at extreme temperature 33,8 ℃ for power transformers [Annex C, TKK report 3].

Winding	Rating (MVA)	Mode of cooling	No load losses (kW)	Load losses at rated current (kW)	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H	K (for θ_H= 98°C)
Al	16	ONAN	16,1	92,9	5,8	56,4	25,2	115,4	0,865
Cu	20	ONAN	16,8	111,8	6,6	56,4	25,2	115,5	0,867
Al	25	ONAN	21,8	127,7	5,8	56,4	25,2	115,4	0,865
Cu	31,5	ONAN/ ONAF	24,5	143,5	5,8	56,4	25,2	115,4	0,865
Al	40	ONAN/ ONAF	33,5	187,8	5,6	56,4	25,2	115,4	0,865

According to the questionnaire study in 2006 the participating utilities use different ambient temperatures ranging from -40 ºC to 40 ºC for dimensioning the transformers, for instance the outdoor distribution transformers in most cases -40 ºC and indoor transformers 20 ºC, 30 ºC or 40 ºC. The power transformers in the substations have normally been dimensioned based on the ambient temperature of 20 ºC, also the value -40 ºC has been used. The maximum allowed power may vary from 80 % of the rated power for indoor distribution transformers up to 130 % for the pole-mounted transformers.

TKK report 3 in Annex C shows the calculated decrease of the loading rate, when ambient temperature varies from 20 ºC to 40 °C. In the worst case the reduction is 20 %, which is needed when the peak load and long hot weather period occur at the same time.

8. Analysis of results

8.1 Planning of electric power network

The climate change will increase the stresses in electric power network, which again will increase the number of failures and at the same time the total failure duration in the present network unless the reliability improvements are emphasised. The city and urban networks shall be analysed separately from the rural networks. Based on the previous chapters there is no need for more detailed regional separation.

8.1.1 City and urban networks

The city networks are already mostly underground cable networks. Their reliability is even nowadays excellent. In city and urban areas the locations for electric power networks are exactly given in the city planning phase with only few possibilities for changing the routes. Owing to the climate change essential factors are the possible floods in city area and the lightning over voltages [1]. In the coastal areas also rising sea level has to be considered.

In urban areas the bare overhead lines are in use, but in renovation they are often changed into underground cable networks. The same procedure is used for urban cable networks as explained for city areas. The stresses caused by climate are increasing in bare overhead lines in urban areas, which should be taken into account. Still, failures in the present urban networks are considerably fewer than in the rural areas and thus the effect of the change is smaller. In urban areas the outage costs are usually reduced by rapidly attainable fault locations as well as efficient disconnecting of the fault area.

8.1.2 Rural network

The climate change according to the models means a stress and a challenge at the same time especially in rural networks. The reliability of rural distribution should be able to be improved cost-effectively. Significance of the climate change impacts depends finally on the requirements for reliability of the distribution and on the valuation of the interruptions in next decades.

For the time being it is impossible to say exactly what requirements will be set for the distribution during the life time of recently built networks. The following comparison shows how cost-effectiveness in building the different conductor types will change if life-cycle costs of investments are defined based on the latest outage cost research and including the climate change.

The overall costs as a function of the average power of a feeder are presented in Figures 8-1 and 8-2. The cases are a bare overhead line passing through forest, a covered conductor line and an underground cable, length 10 km. Figure 8-1 shows the total costs calculated using the interruption prices of 2006, see Table 6-8 and Figure 8-2 those of year 2003, see Table 8-1. Analysed region is inland and other parameters used in the calculations have been taken from Chapter 6. One has to notice that the power is the mean value. The designations KAH 03 and KAH 06 in Tables 8-2 and 8-3 mean the interruption prices of 2003 and 2006 respectively.

Table 8-1. Interruption prices 2003 [16].

Consumer	**Fault interruption**		**High speed AR**	**Delayed AR**
	€/kW	**€/kWh**	**€/kW**	**€/kW**
Household	0,07	0,61	0,03	0,09
Agriculture	0,54	4,90	0,25	0,70
Industry	2,60	8,70	1,10	2,90
Public	0,65	3,40	0,23	0,73
Service	1,90	11,00	0,95	2,10

Tables 8-2 and 8-3 show the boundary power values of the feeder, which means the minimum value above which a 10 km long bare overhead line is profitable to be changed into covered conductor line or underground cable. Some examples are seen on the Figures 8-1 and 8-2 as the intersection points on the two lines in question. In Tables 8-2 and 8-3 the boundary power values are given for different interruption prices, different predictions as well as for the regions inland and Lapland. In Lapland region the number of the failures is much less than in inland.

Table 8-2. The boundary power values above which a 10 km long bare overhead line is economically profitable to be changed into covered conductor line or underground cable. The region is inland.

Inland	**Boundary power value [kW]**					
	Present situation		**Prediction 1**		**Prediction 2**	
	KAH 03	**KAH 06**	**KAH 03**	**KAH 06**	**KAH 03**	**KAH 06**
Bare overhead line vs. covered conductor	1 150	560	1 070	520	650	310
Bare overhead line vs. ground cable	2 830	1 290	2 540	1 180	1 650	750

Table 8-3. The boundary power values above which a 10 km long bare overhead line is economically profitable to be changed into a covered conductor line or a underground cable. The region is Lapland. KAH 03 and KAH 06 refer to interruption prices of 2003 and 2006.

Lapland	**Boundary power value [kW]**					
	Present situation		**Prediction 1**		**Prediction 2**	
	KAH 03	**KAH 06**	**KAH 03**	**KAH 06**	**KAH 03**	**KAH 06**
Bare overhead line vs. covered conductor	1 650	890	1500	820	1 200	650
Bare overhead line vs. ground cable	4 670	2 540	4 000	2 220	3 220	1 780

The interruption prices of 2006 are 3 to 5 times the corresponding prices of 2003. The increasing outage costs and the increasing number of the failures both tend to decrease the boundary power value.

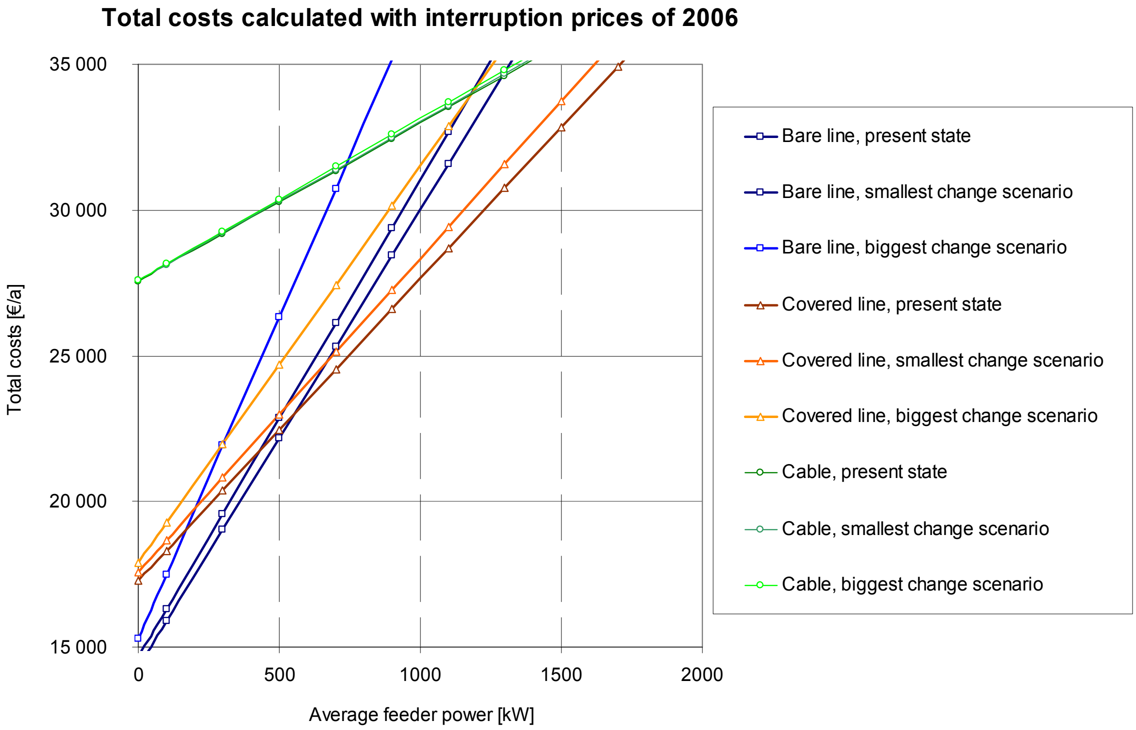


Figure 8-1. Overall costs [€/a] as a function of the average feeder power [kW] in cases of a 10 km long bare overhead line passing through forest, covered conductor line and underground cable. The total costs calculated using interruption prices of 2006.

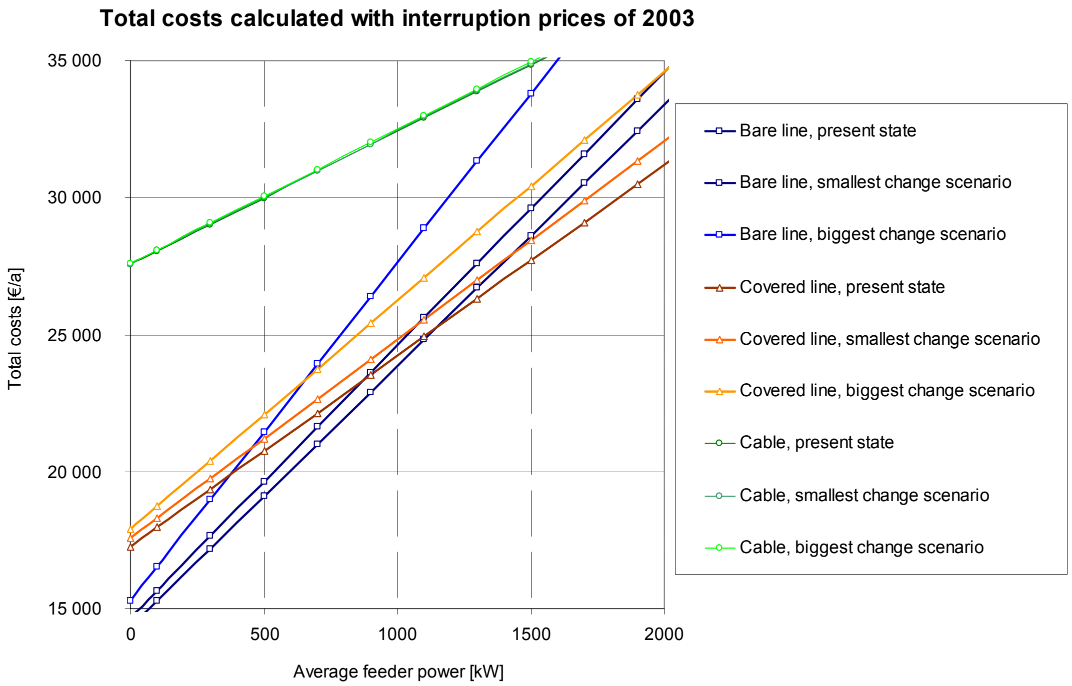


Figure 8-2. Overall costs [€/a] as a function of the average feeder power [kW] in cases of a 10 km long bare overhead line passing through forest, covered conductor line and underground cable. The total costs calculated using interruption prices of 2003.

According to Figures 8-1 and 8-2 as well as Tables 8-2 and 8-3 the outage costs, climate change predictions and number of the failures have extremely high importance in the cost-effective selection of the line type. All these values in question have to be more or less estimated. At this moment it is impossible to give any correct values for those parameters. It is remarkable that in the studied example the boundary power is smaller in calculation with 2006 outage costs and ignoring the climate change than in calculation with 2003 outage costs and considering the *biggest change prediction* of the climate change. In Lapland the power limits are considerably higher than in inland. The main reason is that there is much less failures in Lapland even present-day than in the other regions.

As previously mentioned the parameters used in the calculation have a strong influence on the final solutions. However, the selection of the suitable conductor for rebuilding a typical rural feeder seems to be clear and mostly based on the investment calculations. In rural areas the feeders are often tens of kilometres long and their consumption is relatively low. In that case it is not profitable merely based on the cost accounting to change the bare overhead lines for instance into the covered conductor lines and even less to underground cables. A part of the line often passes through a field or follows the roadside, which again increases the boundary power. Even if the latest interruption prices were used and the climate change according to the biggest change prediction has been adopted into the calculation, the comparison of costs will not in that case lead into a proposal for changing the conductor type.

The climate change shall not be ignored even though the extensive changing of the conductor types is not economically profitable. Thus, other ways shall be found to be prepared for climate change. Instead of changing conductors there are several possibilities for increasing the reliability of the distribution. One solution worth consideration is to move the overhead lines passing through a forest into the roadside. Rebuilding using this means is already widely used. It is assumed that the cost for building on the roadside is the same as for building in the former location in forest. Heavy winds often blow from south-west direction, in which case the best location of the lines would be the north-east side of a road. Actually it is not always possible to choose the side of a road for the line.

Other techniques increasing the reliability are not studied here. Profitability of increasing use of disconnectors, circuit breakers, substations or the one kilovolt system depends so strongly upon consumption and network topology as well as on the chosen interruption prices that showing them as an example does not give extra information. A similar trend can be seen in all the investments increasing the reliability: the preventive actions against the climate change impacts tend to increase the profitability of investments, but the cost-effectiveness and the sufficiency of the investment always have to be considered case by case.

Previously the impact of climate change has been described as costs. Many utilities have set their own goals for customer’s outage duration, which is taken into account in developing the network during renovation. The climate change will increase the fault duration in the present network. This is worth considering in the renovation locations, in order to fulfil the reliability requirements even in the future. Reaching the boundary values may need considerable extra investments in some consumption units.

In the renovation locations it is useful to think over how the reliability of distribution can be improved later on when climate conditions are changing. Would it be possible to reduce failures quite easily by adding components like disconnectors or circuit breakers with a remote control. Other alternatives could be changing the line into more secure structure or perhaps building a new substation.

Strong and extreme weather conditions are for instance the unexceptional temperatures lying within first or last two percents of the 100-year statistics. The increased precipitation or heavy storms are regarded as extreme conditions, too. These conditions tend to increase in conjunction with the climate change. Even though the extreme conditions strengthen with climate change, their prediction is very difficult. Medium voltage lines in rural areas are very sensitive for strong winds or heavy snow load phenomena. If one wants to protect efficiently the electric network against these weather conditions, one alternative would be the clearing of the overhead line routes in the same way as in case of transmission lines. This would strongly increase the investment expenses. Moreover, the permissions from forest owners for widening the routes would be difficult to achieve. Power quality improvement cannot be used as an argument, because the forest owner is not necessarily a consumer of the distribution network in question. Another efficient alternative for preventing wide interruptions caused by extreme conditions is the underground cabling. In rural areas the cable network is not widely used, which would mean replacing the present overhead line network by underground cables during renovations. Based on the present knowledge the climate will not change into such stormy or easily snow loaded, that underground cable would be economically profitable in rural feeders, which are typically long and their consumption is low. The cost-effectiveness of cable utilisation increases with increasing power consumption.

Based on high investment costs the failures are impossible to be prevented cost-effectively. Thus it is reasonable to try to minimise the disadvantage caused by a large scale failure i.e. by the duration of several simultaneous faults. Several utilities make efforts to shorten the interruption duration in possible large scale failures for instance by increasing the repair personnel. This includes agreements with foresters and forest machine owner's and their training. Possibilities for disconnecting fault areas or increasing of substations will also shorten the interruption duration. When consumption increases the utilisation of underground cables may become cost-effective.

As a summary: Based on the climate change predictions and calculated expenses, there will be no chances in preparing for the extreme conditions compared to the present circumstances. In rural areas a consumer has to be ready for a power-failure. If long duration interruptions are not acceptable the most economical solution is to purchase a reserve power system. Intensive information and guidance are recommended for utilities as a part of preparing for climate change. The situation will be changed, if much higher requirements are set for reliability of distribution in determining the fixed compensation basis and its amount. In this case the network tariff will rise due to extra investments and this should be accepted by customers. Most customers living in rural areas are now quite satisfied with the power quality.

In rural areas it is recommended to pay attention to the increasing expenses and fault durations as well as the snow loads in overhead line structures. Based on the climate models the snow load generation is not expected to increase in coastal regions. In predictions the temperature will rise above zero more often than nowadays and thus the ice and snow loads cannot grow too heavy due to melting in between. The case is not the same in the regions suffering from the snow loads even nowadays. These regions are Vaara-Suomi and other areas gathering snow. In these areas attention shall be paid to the strength of overhead line structures and a careful clearing of the line routes.

8.2 Building of electric power network

The most remarkable climate change factor in building of electric power network consists of the changes in ground freezing. This concerns mainly soft soils in coastal and southern Finland. Pole erection works will become difficult when the ground frost decreases. Machines, which are able to move in soft terrain can be found, but deep traces on the soft soil are often not accepted by the landowners. On the other hand the developing technique should in the future offer a change to pole erecting work even on unfrozen ground. Decreasing ground frost concerns even other fields of activity, such as forest machines moving in the hardwood swamps.

The utilities prepare for the climate change in a different way depending on the operating environment and their goal setting. In the regions having a high increase of consumption the real lifetime of the network is often remarkably shorter than the technical lifetime. When the service life of the network is relatively short, it is easier to prepare for changing circumstances. On the other hand the underground cables are often used, in which case the climate change does not have such a strong impact. In the regions where the networks are intended to be maintained until the end of the service time, the climate change has to be considered more carefully as the climate will be changing according to the predictions for next 50 years. The utilities having their own requirements for the number of outages and outage duration, the climate change has to be observed for assuring the sufficiency of the reliability increasing investments.

9. Summary

Stresses increase with the climate change which increases the number of faults in the present network and at the same time the overall failure duration unless some efforts for improving the reliability will be done. The impact is remarkable especially in overhead rural networks passing through the forest. Based on the calculations the influence of climate change is much lower at the roadside and even lower in the fields. Urban networks are already mostly underground cable networks having considerably lower climate effects compared to rural overhead lines. When the climate change influence is studied as costs, their proportion from overall costs is finally small with the parameters used in the calculations.

The utilities emphasise the reliability of distribution and the present methods are in several regions sufficient even in the climate change. A good renovation alternative is to move a long and low-consumption line typical in rural areas to the roadside even in a climate change case. When line lengths are shortening and power consumption is increasing it may be profitable to use also underground cables in many areas. The climate change mostly increases the profitability of the reliability improving investments, but cost-effectiveness and sufficiency in the reliability goals always require a case-specific study. Additionally, in the areas sensitive to snow loads it is worth to concentrate on clearing the routes and to assure the strength of the structures to withstand snow loads.

The final consequences of climate change need to be studied using case-specific parameters, because the weather causes faults in various ways depending on the ambient conditions. In most cases the climate change impact is remarkable especially in the regions that are nowadays sensitive to weather conditions. The repair time will be increased if roads and routes are in poor conditions. On the other hand the number of faults will increase in a forest which is sensitive to the weather conditions.

The climate change gives reason for a customer service orientation: open-minded information and guiding in fault conditions as well as services like devices for over-voltage protection, uninterrupted power supply or reserve power. The utilities aiming at a low number and short total duration of outages have to assure the sufficiency of the reliability increasing investments in climate change conditions.

The additional costs due to the climate change are relatively low, in the worst case around 10 %, compared to the total costs. The predicted total duration of the interruptions will increase from 60 % to 80 % in case of both covered and bare overhead lines passing through the forest. The portion of the overhead lines have been decreasing for some years, the effect is not yet seen in the interruption statistics. A careful study of the improvements is needed especially for the vulnerable parts of the electric distribution network.

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Common note: the above mentioned web pages have been referred in May–August 2007.

Reports and publications

In this project the following reports have been drawn up:

- Martikainen, A., Pykälä, M.-L., Farin, J. Recognizing Climate Change in Electricity Network Design and Construction, VTT.

- Hashmi, G.M., Millar, R.J., Lehtonen, M. Cable ampacity analysis for MV underground networks laid in thermally unstable environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology.

- Hashmi, G.M., Millar, R.J., Lehtonen, M. Cable ampacity analysis for LV underground networks laid in thermally unstable environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology.

- Hashmi, G.M., Millar, R.J., Lehtonen, M. Transformers Loading Conditions for Fu-ture Thermally Unstable Environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology.

Additionally, an article in the annual of the ClimBus programme and a poster in the ClimBus seminar were published:

- Syri, S. Martikainen, A., Lehtonen, M. Ilmastonmuutoksen huomioiminen sähköverkon suunnittelussa ja rakentamisessa, Climbus Annual 2007.

Martikainen, A., Pykälä, M.-L., Hashmi, G.M., Millar, R.J., Lehtonen, M. Ilmastonmuutoksen huomioiminen sähköverkon suunnittelussa ja rakentamisessa, poster in the Climbus Seminar 2007.

Annex A: Equations used in calculations

Equations for the example of the climate change impact are presented in Chapter 6

The present value of costs is calculated:

$$A = \frac{k_1}{1+i} + \frac{k_2}{(1+i)^2} + ... + \frac{k_n}{(1+i)^n}\,, \qquad (1)$$

in which i = rate of interest [percent/100]
n = time of payment [a]
k = yearly cost [€].

The yearly cost is calculated using the annuity method:

$$S = A \cdot \frac{i}{1-(1+i)^{-n}}\,, \qquad (2)$$

in which A = present value [€]
i = rate of interest [percent/100]
n = operating time [a].

Calculation example for the current value and yearly costs of clearing:

Rate of interest is 5 %
Interval between clearings 16 years
Single costs of clearing of a 10 km long line 12 000 €.

The current value of clearing:

$$A = \frac{12000€}{1{,}05^{16}} + \frac{12000€}{1{,}05^{32}} = 8015€$$

The yearly costs of clearing:

$$S = 8015\,€ \cdot \frac{0{,}05}{1-(1+0{,}05)^{-40}} = 467\,€$$

The yearly fault reparation costs are calculated using the equation:

$$K = K_{fault} \cdot f_{fault} \qquad (3)$$

in which K = single fault reparation cost [€]
f = fault rate [number of faults/a].

The yearly interruption (KAH) costs caused by failures are calculated using the equation:

$$KAH = (f \cdot P \cdot k_{\mathrm{p}} + t \cdot P \cdot k_{\mathrm{e}}), \qquad (4)$$

in which f = number of interruptions for a customer in a year [events/a]
P = average consumption of a consumer group [kW]
k_p = interruption cost valuation [€/kW, events, a]
t = interruption duration for a customer in a year [h/a]
k_e = interruption cost valuation [€/kWh, a].

Annex B: Instructions in Finnish

OHJE:

Ilmastonmuutoksen huomioiminen sähköverkon suunnittelussa ja rakentamisessa

SISÄLLYSLUETTELO

LIITTEET

Liite 1: Ilmastonmuutosennusteet

Liite 2: Maakaapeleiden kuormitettavuus

Liite 3: Muuntajien kuormitettavuus

1. JOHDANTO

Ohjeistus perustuu VTT:llä tehtyihin tutkimuksiin:

- Recognizing climate change in electricity network design and construction; report
- Ilmastonmuutoksen vaikutus sähköverkkoliiketoimintaan; raportin viite [1]

sekä TKK:lla tehtyihin tutkimuksiin

- Cable ampacity analysis for MV underground networks laid in thermally unstable environments; Annex C, TKK raportti 1.
- Cable ampacity analysis for LV underground networks laid in thermally unstable environments; Annex C, TKK raportti 2.
- Transformers Loading Conditions for Future Thermally Unstable Environments; Annex C, TKK raportti 3.

Ohjeistuksessa esitetään

a) miten ilmasto ilmastomallien mukaan muuttuu sähköverkkojen kannalta vertailujaksolta 1961–1990 ajanjaksoon 2016–2045 verrattuna

b) mikä on ilmastonmuutoksen merkitys sähköverkoissa, sekä

c) ehdotuksia, siitä miten ilmastonmuutokseen tulisi varautua.

2. ILMASTONMUUTOS SÄHKÖVERKON KANNALTA

Seuraavat sääilmiöt aiheuttavat merkittävimmät vaikutukset vikamääriin: *tuuli ja myrsky, ukkonen*, *lumi- ja jääkuorma* sekä *lumikuorman kaatama puu*.

Tuuli ja myrsky aiheuttavat vikoja pääasiassa kaatamalla puita sekä taivuttamalla ja lennättämällä oksia sähköverkon päälle. Ukkosen yhteydessä esiintyvät voimakkaat tuulet kuuluvat tähän kategoriaan. Puiden kaatumiseen tuulen voimasta vaikuttaa routa ja puussa oleva lumikuorma siten, että roudattomuus ja lumikuorma lisäävät tuulenkaatoja. Tuulen ja myrskyn aiheuttamien vikamäärien arvot perustuvat ennustettuihin tuulen, sadannan, roudan ja lämpötilan muutoksiin.

Ukkosen aiheuttamat viat johtuvat salamoiden aiheuttamista ylijännitteistä. Ylijännitteet vaurioittavat pääasiassa johtimia ja muuntajia. Ukkosen aiheuttamien vikamäärien arvot perustuvat suoraan ukkosmäärien muutosennusteisiin.

Lumi- ja jääkuorma tarkoittaa johdolla ja muissa rakenteissa olevaa lunta ja jäätä. Lumi ja jää kertyvät johdoille tavallisesti huurteen aiheuttamasta tykystä. Tämä aiheuttaa mekaanista rasitusta painamalla johtimia voimakkaasti. Johtimien painuminen aiheuttaa vetoa erityisesti kulmapylväisiin ja voi siten aiheuttaa pylväiden kaatumisia tai katkeamisia. Johtimet voivat painua tykkykuormassa alaspäin niin paljon, että ne koskettavat yhteispylvästapauksissa alapuolella olevia johtoja tai aluskasvillisuutta. Myös tuuli voi helposti heilauttaa tykkykuormassa olevat johtimet yhteen. Tykky voi myös vaurioittaa johdinta niin, ettei vika välttämättä synny heti, vaan saattaa ilmaantua yllättäen myöhemmin. Muita lumi- ja jääkuormasta vikaantuvia rakenteita ovat tavallisesti suojaamattomat pylväänpäässä olevat erottimet. Erityisen haitallinen on ilmiö, jossa ensin sataa märkää lunta ja tämän jälkeen lämpötila laskee pakkasen puolelle jäädyttäen märän lumen laitteen ympärille. Lumi- ja jääkuorman aiheuttamien vikamäärien arvot perustuvat huurteessa, sadannassa ja lämpötilassa tapahtuviin muutoksiin.

Lumikuorman kaatama puu johtuu lumen ja jään taivuttamista tai kaatamista puista. Usein lumikuorman taivuttamat puut ovat helposti taipuvia notkeita lehtipuita, mutta myös suuret puut voivat kaatua lumikuorman painon alla. Tässä tapauksessa vikamäärien arvot perustuvat huurteessa, sadannassa, lämpötilassa ja roudassa tapahtuviin muutoksiin. Huurteen ja sadannan lisääntyminen lisäävät rasitusta. Lämpötilan nousu lisää vikatapauksia niin pitkään kun sadanta tulee jäänä, räntänä tai lumena. Roudan vähentyminen lisää lumikuorman aiheuttamia puunkaatoja, ja sitä kautta viat lisääntyvät.

Suomi on pohjois-eteläsuunnassa pitkä maa ja ilmastossa on eroja Pohjois- ja Etelä-Suomen välillä. Tämä on otettu huomioon jakamalla Suomi kuvan B1 mukaisesti. Aluejaon perusteena ovat ilmastonmuutosennusteet ja vikatilastot.

Kuva B1. Aluejako.

Ilmastonmuutosennusteissa on epävarmuutta ja tätä pyritään arvioimaan esittämällä eri sääilmiöiden muutosten vaikutus kahden eri ennusteen[2] avulla:

- Ennuste 1 = pienin muutosennuste
- Ennuste 2 = suurin muutosennuste.

Taulukoissa B1–B4 on esitetty merkittävimpien vianaiheuttajien suhteelliset arvot alueittain ajanjaksolle 2016–2045. Tietyissä tapauksissa pienin muutosennuste saattaa näyttää rasitusten pienenemistä. Kuitenkin kaikessa rakentamisessa on järkevää pitää voimassa vähintään nykyinen taso ilmastonmuutokseen varautumisessa.

Taulukko B1. Merkittävimpien vianaiheuttajien suhteelliset arvot eteläisellä rannikolla ajanjaksolla 2016–2045. Nykytilanne vastaa arvoa 1.

Sääilmiö	**Rannikko eteläinen**	
	Ennuste 1	**Ennuste 2**
Tuuli ja myrsky	1,0	2,0
Ukkonen	1,2	1,5
Lumi- ja jääkuorma	1,0	1,3
Lumikuorman kaatama puu	1,0	1,3

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[2] Tutkimuksessa [1] määritettiin ilmastomallien antamien ennusteiden perusteella ilmastomuuttujien muutosennusteet ajanjaksolta 1961–1990 vuosille 2016–2045. Muutosennusteet perustuvat neljän eri simulaation tuloksiin ja näistä tuloksista ennuste 1 vastaa pienintä muutosennustetta ja ennuste 2 puolestaan suurinta muutosennustetta. On huomattava, että ennusteet koskevat 30 vuoden ajanjaksoa, eivät minkään yksittäisen vuoden ilmastoa. Tällöin vuosittaiset poikkeamat voivat olla hyvinkin suuria.

Taulukko B2. Merkittävimpien vianaiheuttajien suhteelliset muutokset pohjoisella rannikolla ajanjaksolla 2016–2045. Nykytilanne vastaa arvoa 1.

Sääilmiö	**Rannikko pohjoinen**	
	Ennuste 1	**Ennuste 2**
Tuuli ja myrsky	1,0	2,5
Ukkonen	1,2	1,6
Lumi- ja jääkuorma	1,0	1,4
Lumikuorman kaatama puu	1,1	1,4

Taulukko B3. Merkittävimpien vianaiheuttajien suhteelliset muutokset Sisä-Suomen alueella ajanjaksolla 2016–2045. Nykytilanne vastaa arvoa 1. Lumi ja jääkuorma sekä lumikuorman kaatamaan puun tapauksissa ennusteen 2 kohdalla on kaksi arvoa, joista suluissa oleva kuvaa muutosta vaara-alueilla yli 250 metrin korkeudella.

Sääilmiö	**Sisä-Suomi**	
	Ennuste 1	**Ennuste 2**
Tuuli ja myrsky	1,0	2,0
Ukkonen	1,2	1,6
Lumi- ja jääkuorma	1,0	1,3 (2,0)
Lumikuorman kaatama puu	1,1	1,4 (2,0)

Taulukko B4. Merkittävimpien vianaiheuttajien suhteelliset muutokset Lapissa ajanjaksolla 2016–2045. Nykytilanne vastaa arvoa 1. Lumi ja jääkuorma sekä lumikuorman kaatamaan puun tapauksissa ennusteen 2 kohdalla on kaksi arvoa, joista suluissa oleva kuvaa muutosta vaara-alueilla yli 250 metrin korkeudella.

Sääilmiö	**Lappi**	
	Ennuste 1	**Ennuste 2**
Tuuli ja myrsky	1,1	1,8
Ukkonen	1,2	1,5
Lumi- ja jääkuorma	1,0	1,0 (2,0)
Lumikuorman kaatama puu	1,1	1,3

Taulukoissa olevilla arvoilla tarkoitetaan siis vikamäärien muutosennusteita. Esimerkiksi Lapissa tuulen ja myrskyn aiheuttamat vikamäärät kasvavat pienimmässä muutosennusteessa 1,1-kertaisiksi ja suurimmassa muutosennusteessa 1,8-kertaisiksi nykytilanteesta ajanjaksoon 2016–2045 verrattuna.

Erot ennusteiden välillä ovat suuret. Täytyy kuitenkin ottaa huomioon, että sää aiheuttaa eri tavalla vikoja riippuen ympäristöolosuhteista. Esimerkiksi mäkinen maasto ja lehtipuuvaltainen metsä lisäävät huomattavasti ilmaston aiheuttamien vikojen määrää avojohtoverkoissa verrattuna avoimessa maastossa kulkevaan vastaavanlaiseen johtoon. Pääsääntöisesti ilmastonmuutoksen vaikutus on huomattava erityisesti jo nykyisin säälle herkillä alueilla. Esimerkiksi huonot kulkuyhteydet lisäävät korjausaikaa ja säälle herkkä puusto lisää vikamääriä. Tällaisilla alueilla ilmastonmuutos korostuu. Näin ollen suurinta muutosennustetta voisi soveltaa pienellä varauksella säälle hyvin herkillä alueilla ja pienintä muutosennustetta puolestaan vähemmän vikaherkillä alueilla.

Edellä mainittujen lisäksi on paikallisia ilmaston aiheuttamia vaikutuksia. Sadannan ja kosteuden lisääntyessä lahon aiheuttamat vauriot voivat lisääntyä. Erityisesti savi- ja hiesumaat pehmenevät kosteuden lisääntyessä huomattavasti ja tämä voi heikentää pylväiden perustuksia. Myös paikalliset maanvyöryt ovat jyrkillä rinteillä mahdollisia. Mahdollisten rankkasateiden aiheuttamat kaupunkitulvat ja jokien tulvimiset tulisi ottaa huomioon muuntajien ja muiden vedelle herkkien rakenteiden sijoittelussa. Rannikolla ja saaristossa, meren läheisyydessä, kannattaa rakenteiden sijoittelussa lisäksi huomata mahdollinen merenpinnan nousu. Roudattomuus ei tavallisesti aiheuta ongelmia, mutta jos sulamista ja jäätymistä tapahtuu useita kertoja vuoden aikana, voi maan liikkuminen aiheuttaa tukirakenteiden heikkenemistä. Edellä mainitut ovat pääsääntöisesti paikallisia ilmiöitä. Ne on kuitenkin syytä ottaa maastosuunnittelun yhteydessä mahdollisuuksien mukaan huomioon, koska jos tietyllä paikalla tällä hetkellä edellä mainittuja ilmaston aiheuttamia ongelmia, niin nämä ongelmat ilmastonmuutoksen myötä pääsääntöisesti korostuvat.

3. ILMASTONMUUTOKSEN MERKITYS JAKELUVERKOSSA

3.1 Kaupunki- ja taajamaverkot

Useimpien kaupunkiverkkojen kaapelointiaste on korkea, ja kaupunkiverkkojen jakelun luotettavuus on sään aiheuttamien vikojen kannalta nykytekniikalla erinomaisen hyvä.

Ilmastonmuutoksen kannalta olennaisia huomioita ovat:

- mahdolliset kaupunkitulvat
- ukkosen aiheuttamat ylijännitteet
- rannikolla merenpinnan nousu.

Taajamien maakaapeliverkkoihin pätevät samat näkökohdat kuin kaupungeissa. Taajamien avojohdot ovat alttiita ilmaston aiheuttamille rasituksille yhä enemmän. Nykyiset vikamäärät ovat silti huomattavasti pienemmät taajamissa kuin maaseudun avojohtoverkoissa. Näin ollen muutoksen suuruus on myös pienempi.

Ehdotuksia ilmastonmuutoksen huomioon ottamiseksi kaupunki- ja taajamaverkoissa:

- taajamaverkoissa kaapelointiasteen nostaminen
- mahdollisten merenpinnan nousun ja kaupunkitulvien huomiointi rakenteiden sijoittelussa
- riittävät ylijännitesuojaukset
- muuntajien ja kaapeleiden kuormituksen tarkkailu kesällä erityisesti poutaisten hellejaksojen aikana (LIITE B2 ja B3). Kaapelin osalta pahin tilanne on maan ollessa kuiva, tällöin kaapelin kuormitettavuus voi laskea alle puoleen nimellisestä. Muuntajan kuormitettavuuteen on kiinnitettävä huomiota, jos pitkä hellejakso ja kuormitushuippu osuvat samaan aikaan.

3.2 Maaseutuverkko

Mallien mukaan ilmastonmuutos lisää selkeästi rasitusta maaseudun päällystämättömissä avojohtoverkoissa. Ilmastonmuutoksen myötä vikamäärät nykyverkossa kasvavat. Tämä kasvattaa vikakustannuksia ja vika-aikoja ellei luotettavuutta parantavia panostuksia lisätä.

Tarkasteltaessa kokonaiskustannuksia ovat vikakustannukset kuitenkin kohtuullisen pieni kustannuserä. Tällöin myös ilmastonmuutoksen lopullinen vaikutus on kokonaiskustannuksissa pieni, vaikka erityisesti suurimmassa muutosennusteessa vikamäärät kasvavat huomattavasti, katso taulukko B5. Lopullinen ilmastonmuutoksen merkityksen suuruus riippuu siitä, mitkä ovat jakelun luotettavuuden vaatimukset ja keskeytysten arvostus. Luotettavuusvaatimusten ja keskeytysten arvostuksen kasvaessa ilmastonmuutoksen vaikutus korostuu.

Taulukko B5. Päällystämättömän avojohdon kokonaisvuosikustannukset [k€/a] alueittain eri maasto-olosuhteissa. Suluissa olevat arvot ovat yli 250 metriä merenpinnasta olevien vaara-alueiden arvoja. Johtopituus 10 km. Lähtöarvot on esitetty raportissa.

	Päällystämätön avojohto yhteenlasketut vuosikustannukset [k€/a]								
	Nykytilanne			**Ennuste 1**			**Ennuste 2**		
	Pelto	**Metsä**	**Tienv.**	**Pelto**	**Metsä**	**Tienv.**	**Pelto**	**Metsä**	**Tienv.**
Rannikko, eteläinen	13,9	15,7	14,7	13,9	16,1	15,0	14,0	16,9	15,4
Rannikko, pohjoinen	13,9	15,7	14,7	13,9	16,1	15,0	14,1	17,3	15,6
Sisä-Suomi	13,8	16,0	14,8	13,9	16,4	15,1	14,0 (14,1)	17,6 (17,8)	15,7 (15,8)
Lappi	13,6	14,8	14,2	13,6	15,2	14,5	13,7 (13,8)	15,4 (15,5)	14,6 (14,7)

Ilmastonmuutoksen merkitys ja siihen varautuminen on tarkasteltava tapauskohtaisesti. Tarkastelussa tulisi huomioida verkon rakenne ja kuormitus sekä ympäristöolosuhteet. Pääsääntöisesti merkittävin ilmastonmuutoksen haitta on niillä alueilla ja niissä rakenteissa, joissa jo tällä hetkellä esiintyy enemmälti sään aiheuttamia ongelmia.

Suurimman ja pienimmän muutosennusteen perusteella arvioiduissa vianaiheuttajien suhteellisissa muutoksissa on erittäin suuret erot, ks. taulukot B1-B4. Tämä kuvastaa hyvin ilmastonmuutoksen vaikutusten ennustamiseen liittyvää epävarmuutta. Näyttää kuitenkin siltä, että ilmastonmuutoksen lopullinen merkitys jää pieneksi maaseutuverkossa. Tyypillinen maaseudun johtolähtö on kymmeniä kilometrejä pitkä päällystämätön avojohto suhteellisen pienellä kulutuksella. Tällaisilla johtolähdöillä johdon investointikustannus on selkeästi suurin kustannuskomponentti, jolloin vikakustannusten (ml. keskeytysten arvostukset) tulisi nousta hyvin huomattavasti, jotta johdin kannattaisi vaihtaa oletettavasti luotettavampaan ja samalla kalliimpaan rakenteeseen. Ilmastomallien ja arvioiden mukaan, ilmasto ei muutu seuraavien 40 vuoden aikana verkkojen kannalta niin vaikeaksi, että näitä maaseudun pitkiä kirkkaita avojohtoja kannattaisi vaihtaa kustannusten perusteella laajassa mittakaavassa varmempaan johdin rakenteeseen. Kulutuksen ja sähkön laadun arvostuksen kasvaessa sekä johdinpituuden lyhentyessä kannattaa johdinrakenteen suunnittelussa miettiä johtimen rakennetta tarkemmin.

Varteenotettava luotettavuutta parantava saneerausmenetelmä maaseudun pitkille johtolähdöille näyttää raporttiosuuden laskentojen mukaan olevan jo nyt laajasti käytössä oleva tapa siirtää johtimet mahdollisuuksien mukaan tienvarteen. Toinen hyvältä vaikuttava huoltotoimenpide on samoin jo nyt laajasti tiedostettu tarve johdinkatujen huolelliseen raivaukseen ja oksimiseen. Yksittäisistä sääilmiöistä tykyn muodostuminen voi tulla paikoitellen erittäin vaikeaksi ongelmaksi. Tykky kannattaa ottaa huomioon erityisesti niillä alueilla, joilla jo nyt esiintyy tykyn aiheuttamia ongelmia: erityisesti Vaara-Suomessa ja muilla lunta keräävillä alueilla. Tykkyyn varautumisessa mahdollisia rakenteellisia vaihtoehtoja ovat muun muassa johtimien siirto tienvarteen ja PAS-johtimien käyttö. Kunnossapitoon liittyen huolellinen raivaus ja oksiminen sekä talviaikaan sään seuraaminen ja tykylle otollisten sääilmiöiden aikana linjapartiointi sekä mahdollisesti helikopterin käyttö. Raivaustyön aloittamista nopeuttaa tiedonsaannin parantaminen tykkylumialueiden paikantamiseksi esimerkiksi pyytämällä yleisövihjeitä paikallislehtien, radion ja internetsivujen avulla. Tärkeätä on myös varmistaa rakenteiden riittävä lujuus tykkylumikuormia vastaan. Esimerkiksi erityisesti kulmapylväisiin kohdistuu suuria rasituksia tykyn kertyessä johtimiin.

Paikallisesti on usein jo tiedossa vialle alttiit verkonosat, kuten harjualueilla esiintyvien rankkojen raekuurojen ja myrskyjen esiintymisalueet. Näihin alueisiin on mahdollista varautua jo ennakolta.

Monissa verkkoyhtiöissä on asetettu omia tavoitteita asiakkaiden kokemille keskeytysajoille ja verkkoja pyritään kehittämään saneerauksien yhteydessä myös näiden tavoitteiden mukaisesti. Ilmastonmuutoksen myötä vika-ajat kasvavat nykyverkossa, taulukko B6. Tämä tulisi ottaa huomioon saneerauskohteissa, jotta jakelun luotettavuudelle asetetut tavoitteet täyttyvät myös tulevaisuudessa. Luotettavuuden raja-arvojen saavuttaminen voi osassa kulutuskohteita vaatia huomattavia lisäinvestointeja.

Taulukko B6. Yhteenlasketut päällystämättömän avojohdon vika-ajat vuodessa [h/a] alueittain, eri maasto-olosuhteissa. Suluissa olevat arvot ovat yli 250 metriä merenpinnasta olevien vaara-alueiden arvoja. Johtopituus 10 km. Lähtöarvot on esitetty raporttiosuudessa.

	Päällystämätön avojohto vika-ajat vuodessa [h/a]								
	Nykytilanne			**Ennuste 1**			**Ennuste 2**		
	Pelto	**Metsä**	**Tienv.**	**Pelto**	**Metsä**	**Tienv.**	**Pelto**	**Metsä**	**Tienv.**
Rannikko, eteläinen	0,16	0,60	0,23	0,17	0,61	0,24	0,18	0,87	0,31
Rannikko, pohjoinen	0,16	0,60	0,23	0,17	0,62	0,24	0,18	1,00	0,34
Sisä-Suomi	0,16	0,75	0,27	0,17	0,77	0,28	0,19 (0,20)	1,16 (1,24)	0,38 (0,41)
Lappi	0,10	0,26	0,12	0,11	0,28	0,12	0,11 (0,12)	0,32 (0,35)	0,14 (0,15)

Ääri-ilmiöt:

Sähkönjakelun kannalta ääri-ilmiöitä ovat vaikeat laajat tykkylumi-ilmiöt sekä laajat puunkaadot voimakkaiden tuulten ja ukkospilvien alla tapahtuvien syöksyvirtausten yhteydessä. Ääri-ilmiöiden ennustaminen on hyvin vaikeaa, mutta arvioiden mukaan ääri-ilmiöt yleistyvät ilmastonmuutoksen myötä. Esimerkiksi lumisateen määrän ennustetaan yleisesti ottaen vähenevän, mutta erittäin rankkoja lumisateita esiintyy tulevaisuudessa nykyistä enemmän.

Käytännössä ainoa tehokas suojautuminen näitä ilmaston ääri-ilmiöitä vastaan on maakaapelointi. Kuten jo aiemmin todettiin, maaseudun keskijänniteverkon laaja maakaapelointi ei tule olemaan nykytietämyksellä kustannustehokasta. Maakaapelin investointikustannus on yksinkertaisesti liian suuri nykyhinnoilla päällystämättömään avojohtoon verrattuna. Maakaapelin käyttö kasvattaa maakapasitanssia ja johdinten välistä kapasitanssia verrattuna avojohtorakenteeseen. Pitkät kaapeliyhteydet edellyttävät loistehon kompensointia. Lisäksi paikoin hyvin kallioinen maaperä tekee kaapeloinnin käytännössä mahdottomaksi. Eli ääri-ilmiöihin varautumiseen ei tule ilmastonmuutosennusteiden mukaan muutoksia nykyiseen tilanteeseen verrattuna. Maaseudulla kuluttajan on varauduttava sähkökatkoksiin, ja jos pidempi aikaisia katkoksia ei voida sallia, on kustannustehokkainta hankkia varavoimajärjestelmä.

Koska ääri-ilmiöiden aiheuttaman uhkan täydellinen ehkäisy on kustannusten perusteella mahdoton toteuttaa, on tällöin järkevää pyrkiä pienentämään mahdollisen suurhäiriön aiheuttamaa haittaa eli usean yhtäaikaisen vian kestoaikoja. Useissa verkkoyhtiöissä panostetaan keskeytysaikojen lyhentämiseen mahdollisissa suurhäiriöissä esimerkiksi lisäämällä mahdollisuuksien mukaan korjaushenkilöstöä tekemällä esimerkiksi metsureiden ja metsäkoneyrittäjien kanssa sopimuksia ja lisäämällä näiden koulutusta. Keskeytysaikojen lyhentämiseen käytetään myös vikapaikkojen erottelumahdollisuutta lisäämällä erottimia ja maastokatkaisijoita sekä uusia sähköasemia. Kulutuksen kasvaessa maakaapelin käyttö voi olla myös taloudellisesti kannattavaa varsinkin savi/hiekka tai vastaavissa pehmeissä maaperissä.

Verkkoyhtiön kannattaa panostaa tiedottamiseen ja ohjaukseen osana ilmastonmuutokseen varautumista. Tilanne ääri-ilmiöihin varautumisessa muuttuu, jos jakelun luotettavuudelle asetetaan huomattavasti nykyisiä tiukemmat vaatimukset. Näitä voisivat olla vakiokorvausten määräytymisperiaatteiden ja suuruuden muutokset.

Ehdotuksia ilmastonmuutoksen huomioon ottamiseksi maaseutuverkoissa:

- johtimien siirto tienvarteen
- kauko-ohjatut erottimet

- maastokatkaisijat
- sähköasemien lisääminen
- rakenteiden lujuus tykkykuormia vastaan
- ylijännitesuojaus
- huolellinen raivaus ja oksiminen
- erottimien suojaus jäätymistä vastaan.

Keskeytysten arvostuksen kasvaessa kannattaa yleisesti ottaen pyrkiä pienentämään keskeytysaikoja mm. jakamalla jakelualueita pienempiin osiin, erottimien, maastokatkaisijoiden sekä mahdollisuuksien mukaan uusien sähköasemien avulla.

Edellä mainitut ovat ehdotuksia, näiden lisäksi myös muita luotettavuutta parantavia tekniikoita on olemassa. Suunta on sama kaikissa luotettavuutta parantavissa investoinneissa: ilmastonmuutoksen aiheuttamien haittojen ehkäisemistarve lisää investointien kannattavuutta, mutta kannattavuus ja investoinnin riittävyys tavoitteiden saavuttamiseksi on aina tarkasteltava tapauskohtaisesti.

Edellä mainittujen lisäksi ehdotetaan kiinnitettävän huomiota sähköverkon komponenttien kuormitukseen ja mitoitukseen muuttuvissa lämpötila- ja sadeolosuhteissa [Annex C, TKK raportit 1-3]:

- Kaapelin kannalta huonoin vaihtoehto on kuiva turpeinen luonnon maa. Kokeiden mukaan kaapelin kuormitettavuus tällaisessa ympäristössä pienenee alle puoleen ohjeellisesta arvosta. Tämä tilanne on mahdollinen pitkän kuivuuden aikana erityisesti, jos kasvillisuutta on kaapelin läheisyydessä.

- Muuntajan kuormitettavuudesta lämpötilan noustessa on esitetty laskelmat. Kun ympäristön lämpötilan nousee pitkäaikaisesti, muuntajan kuormitusta on syytä pienentää nimellisestä.

3.3 Sähköverkon rakentaminen

Tämän hetkisen tietämyksen mukaan roudan vähentymisellä on merkittävimmät vaikutukset sähköverkkojen rakentamisessa. Erityisesti pylvästystyöt vaikeutuvat pehmeällä maaperällä roudan määrän vähentyessä. Pehmeässä maastossa liikkuvia koneita löytyy, mutta pehmeään maastoon jääviä jälkiä ei useinkaan maanomistajien puolelta hyväksytä. Tosin tekniikan kehittymisen luulisi tarjoavan tulevaisuudessa mahdollisuuden pylvästystöihin myös maan ollessa sula, koska roudan vähentyminen koskettaa muitakin toimialoja, kuten esimerkiksi metsäkoneiden liikkumista metsässä.

4. YHTEENVETO

Ilmastonmuutos ei aiheuta nykytietämyksellä merkittäviä muutoksia sähköverkkojen suunnitteluun. Ilmastonmuutoksen myötä rasitukset kasvavat ja tämä lisää nykyverkossa vikojen määrää, mutta lopullinen vaikutus jää kuitenkin suhteellisen pieneksi. Vaikeimpina sään aiheuttamina ongelmina tulevat olemaan myös jatkossa voimakkaiden tuulien ja tykkylumen aiheuttamat vauriot. Tykky voi olla ilmastonmuutoksen myötä paikoitellen erittäin vaikea ongelma. Tykkylumialueiden kartoittamiseen kannattaa panostaa.

Useissa verkkoyhtiöissä panostetaan jakelun luotettavuuden parantamiseksi ja tämä edesauttaa ilmastonmuutokseen sopeutumisessa. Haastavin kohde ilmastonmuutoksen kannalta ovat maaseudun keskijännitteiset avojohdot, koska näillä johdoilla sään aiheuttamat viat ovat tällä hetkellä yleisimpiä. Vaikka erityisesti suurimmassa muutosennusteessa vikamäärät kasvavat erittäin voimakkaasti, niin tämä ei kuitenkaan näytä johtavan kustannusten perusteella varmemman johdinrakenteen suosimiseen. Päällystettyjen avojohtojen (PAS) tai maakaapeleiden käyttö ei ole laajamittaisesti kustannustehokasta maaseudun hajanaisella kulutuksella. PAS-johdon tai maakaapelin laajamittainen käyttö vähentää sään aiheuttamia vikoja, mutta niiden laajamittainen käyttö tuo esiin muita ongelmia. Esimerkiksi PAS-johdon suojauksessa on kiinnitettävä huomiota maasulussa olevan johtimen havaitsemiseen. Maakaapelilla maakapasitanssin ja johdinten välinen kapasitanssi kasvavat verrattuna avojohtorakenteeseen.

Ilmastonmuutoksen myötä luotettavuutta lisääviä panostuksia tulee kuitenkin lisätä, jotta jakelun luotettavuus saadaan rasitusten kasvaessa pidettyä nykyisellään. Varteenotettavia vaihtoehtoja ovat jo nyt laajasti käytössä olevat saneerausmenetelmät; johtimien siirto tienvarteen, erottimien lisäys, mahdollisesti maastokatkaisijoiden käyttö, huolellinen raivaus ja oksiminen. Kokonaisuutena eri vaihtoehtoja jakelun luotettavuuden parantamiseksi löytyy useita ja tämä helpottaa ilmastonmuutokseen sopeutumista. Eri saneerausvaihtoehtojen kannattavuus on aina tarkasteltava tapauskohtaisesti. Yhteistä on kuitenkin se, että ilmastonmuutos lisää näiden kaikkien luotettavuutta parantavien rakenteiden kannattavuutta.

Kulutuksen kasvaessa ja johtopituuden lyhentyessä ilmastonmuutokseen varautumisen vaikutus alkaa korostua. Tällöin maakaapeli ja PAS-johto tulevat varteenotettaviksi vaihtoehdoiksi paljaalle avojohdolle.

Ilmastonmuutoksen aiheuttamat lisäkustannukset kokonaiskustannuksiin verrattuna ovat suhteellisen alhaiset, pahimmassakin tapauksessa noin 10 %. Keskeytysten kesto kasvaa metsäalueilla 60–80 % sekä päällystetyllä että paljaalla avojohdolla. Avojohtojen osuus on vähentynyt viime vuosina, mutta tämän vaikutus ei vielä näy vikatilastoissa. Vaurioitumiselle alttiiden verkonosien parantamisvaihtoehdot kannattaa tarkastella tapauskohtaisesti.

5. LÄHDELUETTELO

Näiden viitteiden numerointi on sama kuin raporttiosuudessa:

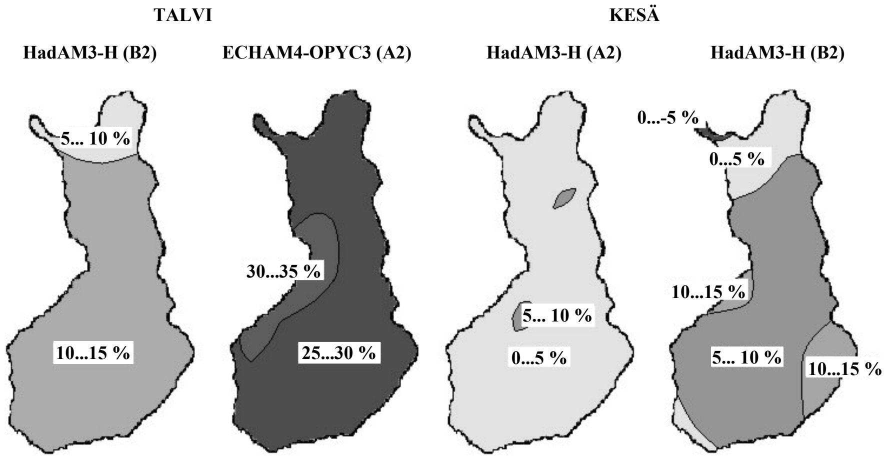
[1] Martikainen, A. Ilmastonmuutoksen vaikutus sähköverkkoliiketoimintaan. VTT Tiedotteita 2338, 2006, 74 s. http://www.vtt.fi/inf/pdf/tiedotteet/2006/T2338.pdf.

[11] Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L.P., Jones, C., Meier, H.E.M., Samuelsson, P., Willén, U. European Climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. Springer-Verlag. ISSN 0930-7575. Climate dynamics 2004, Vol. 22(1) pp. 13–31.

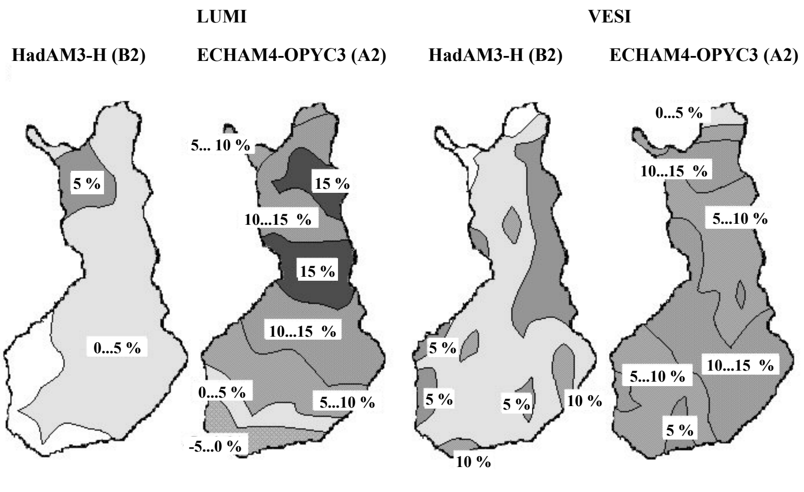
[12] Ruokolainen, L. Kasvihuoneilmiön voimistumisesta johtuvan ilmastonmuutoksen vaikutus sään ääri-ilmiöihin Suomessa (in Finnish). Pro gradu -tutkielma. Helsinki. Helsingin yliopisto, 2005. 74 s.

LIITE B1

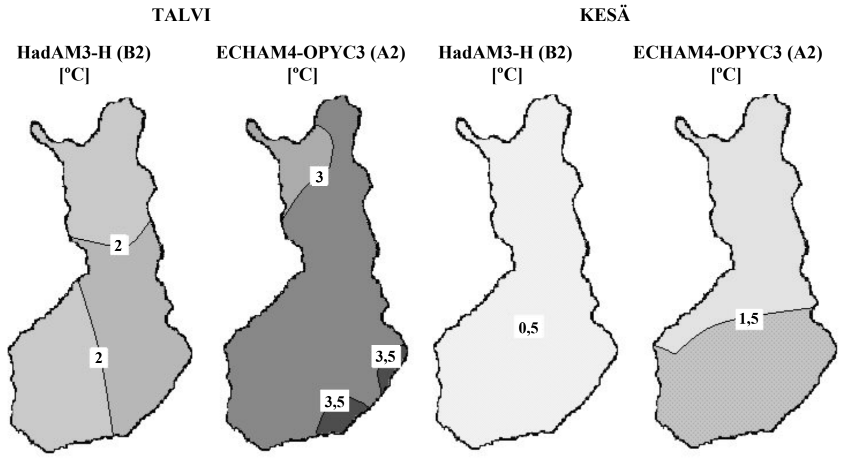
Ilmastonmuutosennusteet nykytilasta (1961–1990) ajanjaksolle (2016–2045). Ennusteiden lähtökohdat ja analyysi on luettavissa tutkimuksesta [1].



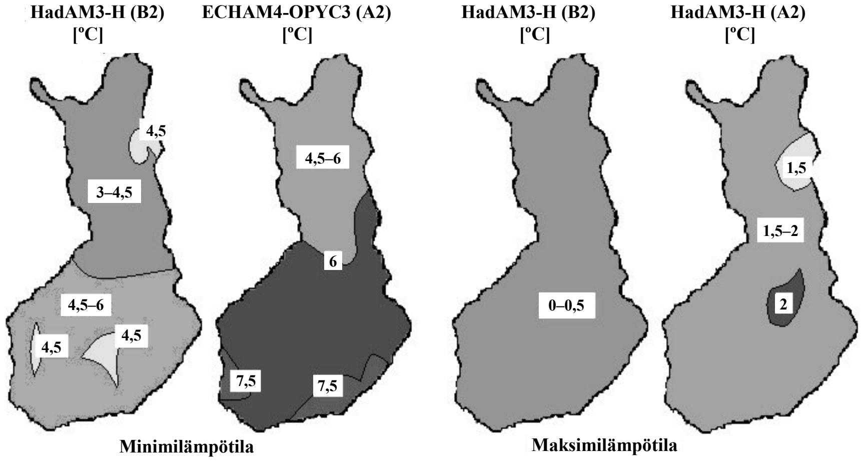
Kuva B1-1. Ilmastomallien antamat ennusteet ajanjakson 2016–2045 talven ja kesän keskimääräisille sadannan muutoksille verrattuna vertailujaksoon. Kuvaparien vasemmanpuoleinen kuva esittää pienintä muutosennustetta ja oikeanpuoleinen suurinta muutosennustetta [11].



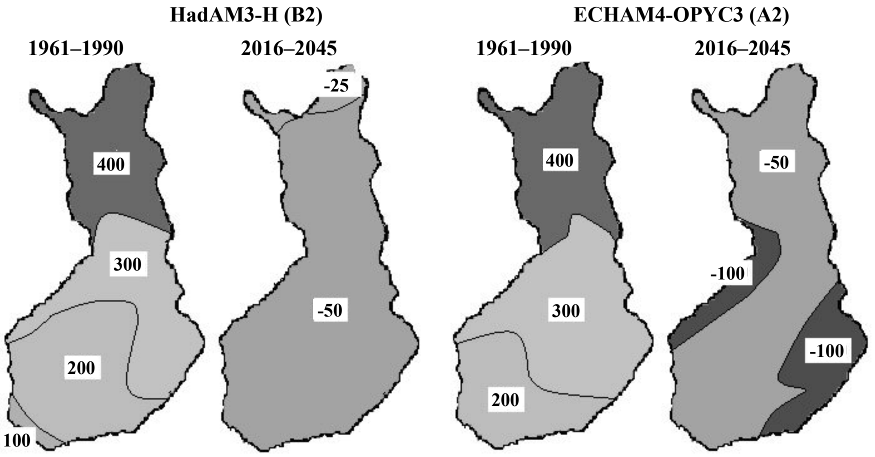
Kuva B1-2. Ilmastomallien antamat ennusteet ajanjakson 2016–2045 kuuden tunnin maksimivesi- ja maksimilumisademäärien muutoksille verrattuna vertailujaksoon. Kuvaparien vasemmanpuoleinen kuva esittää pienintä muutosennustetta ja oikeanpuoleinen suurinta muutosennustetta [12].



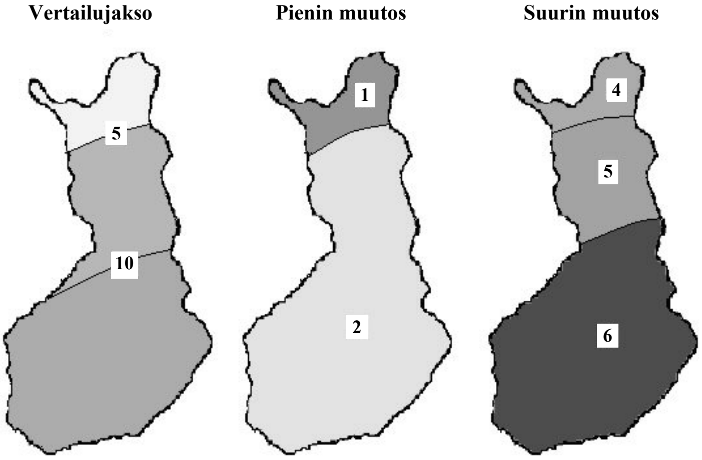
Kuva B1-3. Ilmastomallien antamat ennusteet ajanjakson 2016–2045 talven ja kesän keskimääräisille lämpötilan muutoksille verrattuna vertailujaksoon. Kuvaparien vasemmanpuoleinen kuva esittää pienintä ja oikeanpuoleinen suurinta muutosennustetta [11].



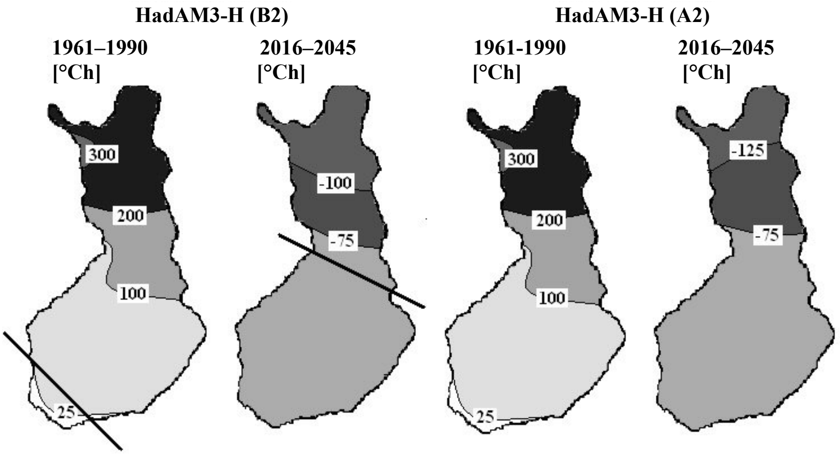
Kuva B1-4. Ilmastomallien antamat ennusteet ajanjakson 2016–2045 minimi- ja maksimilämpötilojen muutoksille verrattuna vertailujaksoon. Kuvaparien vasemmanpuoleinen kuva esittää pienintä ja oikeanpuoleinen suurinta muutosennustetta [12].



Kuva B1-5. Kuuraantumisen keskimääräinen aika tunteina tammikuussa 1961–1990 ja ajanjaksolle 2016–2045 ennustettu keskimääräinen muutos. Vasemmanpuoleinen kuvapari esittää pienintä ja oikeanpuoleinen suurinta muutosennustetta [1].

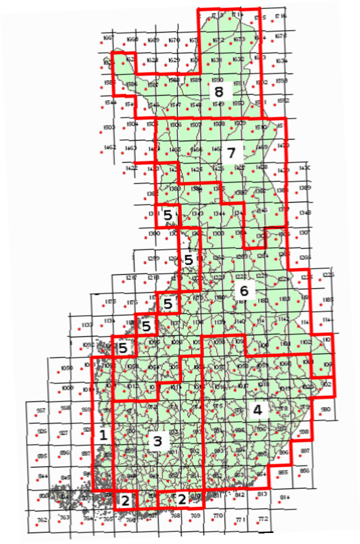


Kuva B1-6. Vallitsevat ukkosmäärät (ukkospäiviä/vuosi) isokeraunisilla tasoilla esitettynä ja lämpötilan muutoksiin perustuvat arviot vuosien 2016–2045 ukkosmäärien muutoksista vertailujaksoon verrattuna [1].



Kuva B1-7. Vuorokauden pakkassumman keskiarvojen isoviivat marraskuussa vertailujaksolla ja ajanjaksolle 2016–2045 ennustettu keskimääräinen muutos. Vasemmanpuoleinen kuvapari esittää pienintä muutosennustetta ja oikeanpuoleinen kuvapari suurinta muutosennustetta. Musta viiva kuvaa routarajaa. Viivan alapuolella maa on sula [1].

Taulukko B1-1. Erittäin suurten tuulen nopeuksien esiintymisen (tuntia/vuosi/ruutu) muutokset. Aluejako on esitetty viereisellä karttapohjalla.



Alue	Pienin muutos-ennuste [%]	Suurin muutos-ennuste [%]
1	-37	89
2	-23	91
3	-26	115
4	-23	44
5	-53	213
6	-100	114
7	25	71
8	7	62

Voimakkaimmat tuulet koetaan tavallisesti syksyllä ja talvella. Vaikka voimakkaiden tuulien esiintyminen pienenee pienimmässä muutosennusteessa, niin tämä ei välttämättä tarkoita tuulen aiheuttamien tuhojen vähentymistä, koska roudan vähentyessä puut kaatuvat talvimyrskyissä helpommin [1].

LIITE B2 Maakaapelit

Keskijännitemaakaapelin AHXAMK-W kuormitettavuus maa- ja putkiasennuksessa erilaisissa maan kosteusolosuhteissa. Taulukoissa luetellaan suhteellinen kuormitettavuus johtimen eri poikkipinnoilla ja kahdella eri johtimen lämpötila-arvolla. Maa-aineksen lämpöresistiivisyys on merkitty tunnuksella ρ_s, jonka yksikkö on km/W = Kelvin · metri/watti. Lämpöresistiivisyys laskelmissa vaihteli arvosta 1,2 km/W (kostea) arvoon 5 km/W (täysin kuiva) [Annex C, TKK raportti 1].

Taulukko B2-1. Kosteuden siirtymisen vaikutus kuormitettavuuteen, maa-asennus kosteassa maassa.

Poikkipinta [mm^2]	**Ei kosteuden siirtymistä ρ_s = 1,2 km/W**	
	Suhteellinen kuormitettavuus	
	65 °C	**90 °C**
70	0,85	0,87
95	0,87	0,87
120	0,87	0,86
150	0,86	0,84
185	0,89	0,83
240	0,88	0,80
300	0,87	0,80

Taulukko B2-2. Kosteuden siirtymisen vaikutus kuormitettavuuteen, maa-asennus tavallisessa täytemaassa (hiekka tai murske) kontrolloitu tilanne.

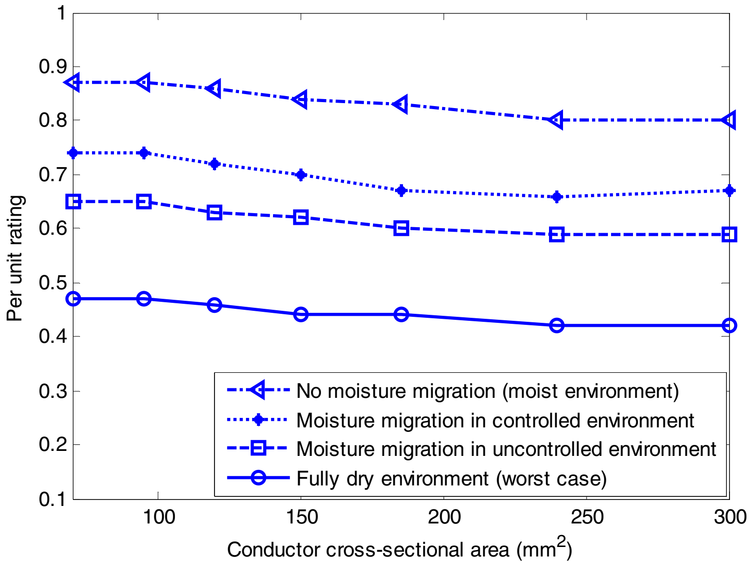
Poikkipinta [mm^2]	**Kosteuden siirtymistä esiintyy, ρ_s arvosta 1,2 km/W arvoon 2,5 km/W**	
	Suhteellinen kuormitettavuus	
	65 °C	**90 °C**
70	0,77	0,74
95	0,78	0,74
120	0,78	0,72
150	0,77	0,70
185	0,79	0,67
240	0,78	0,66
300	0,77	0,67

Taulukko B2-3. Kosteuden siirtymisen vaikutus kuormitettavuuteen, maa-asennus luonnonmaassa, kontrolloimaton tilanne.

Poikkipinta [mm^2]	**Kosteuden siirtymistä esiintyy, ρ_s arvosta 1,2 km/W arvoon 2,5 km/W**	
	Suhteellinen kuormitettavuus	
	65 °C	**90 °C**
70	0,71	0,65
95	0,72	0,65
120	0,72	0,63
150	0,71	0,62
185	0,73	0,60
240	0,72	0,59
300	0,71	0,59

Taulukko B2-4. Kosteuden siirtymisen vaikutus kuormitettavuuteen, maa-asennus täysin kuivassa maassa.

Poikkipinta [mm^2]	**Ei kosteuden siirtymistä $\rho_s = 5$ km/W**	
	65 °C	**90 °C**
70	0,46	0,47
95	0,46	0,47
120	0,47	0,46
150	0,46	0,44
185	0,47	0,44
240	0,46	0,42
300	0,46	0,42



Kuva B2-1. Kuormitettavuuden muutosmaa-asennuksessa eri kosteusarvoilla [Annex C, TKK raportti 1].

Taulukko B2-5. Kosteuden siirtymisen vaikutus kuormitettavuuteen, putkiasennus kosteassa maassa.

Poikkipinta [mm^2]	**Ei kosteuden siirtymistä ρ_s = 1,2 km/W**	
	Suhteellinen kuormitettavuus	
	65 °C	**90 °C**
70	0,74	0,77
95	0,76	0,77
120	0,76	0,76
150	0,75	0,74
185	0,77	0,73
240	0,76	0,70
300	0,76	0,71

Taulukko B2-6. Kosteuden siirtymisen vaikutus kuormitettavuuteen, putkiasennus tavallisessa täytemaassa (hiekka tai murske).

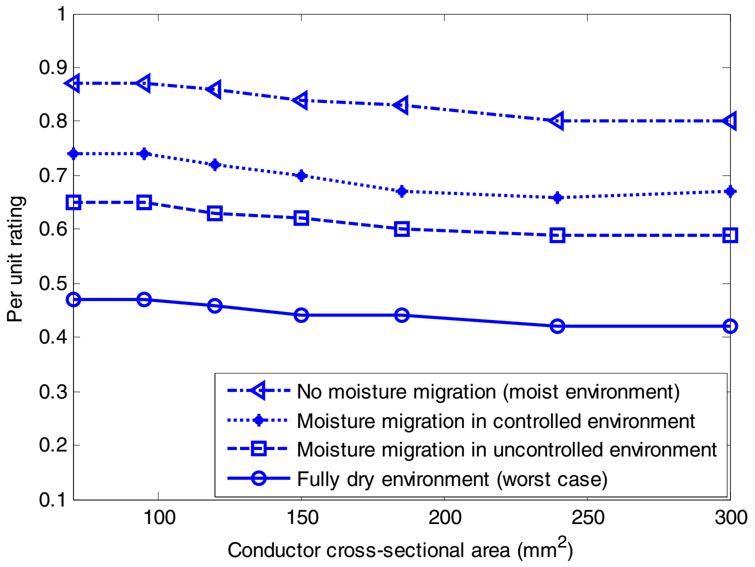
Poikkipinta [mm^2]	**Kosteuden siirtymistä esiintyy, ρ_s arvosta 1,2 km/W arvoon 2,5 km/W**	
	Suhteellinen kuormitettavuus	
	65 °C	**90 °C**
70	0,75	0,73
95	0,76	0,72
120	0,76	0,70
150	0,75	0,69
185	0,77	0,68
240	0,76	0,65
300	0,75	0,66

Taulukko B2-7. Kosteuden siirtymisen vaikutus kuormitettavuuteen, putkiasennus luonnonmaassa, kontrolloimaton tilanne.

Poikkipinta [mm^2]	**Kosteuden siirtymistä esiintyy, ρ_s arvosta 1,2 km/W arvoon 2,5 km/W**	
	Suhteellinen kuormitettavuus	
	65 ºC	**90 ºC**
70	0,75	0,67
95	0,76	0,68
120	0,76	0,66
150	0,75	0,65
185	0,76	0,63
240	0,74	0,60
300	0,74	0,60

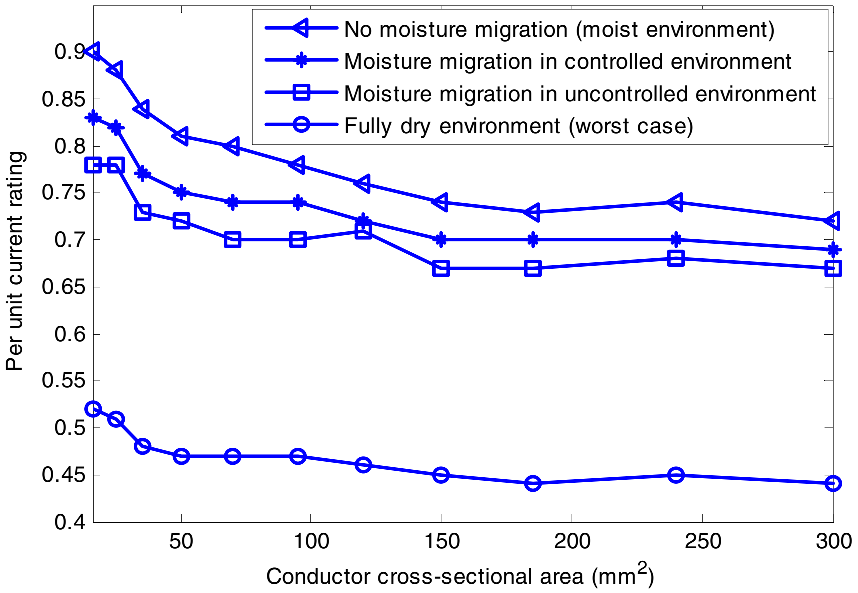
Taulukko B2-8. Kosteuden siirtymisen vaikutus kuormitettavuuteen, putkiasennus täysin kuivassa maassa.

Poikkipinta [mm^2]	**Kosteutta ei siirry – siirtyy, ρ_s = 5 km/W**	
	Suhteellinen kuormitettavuus	
	65 ºC	**90 ºC**
70	0,48–0,49	0,50
95	0,49	0,49-0,50
120	0,49	0,48
150	0,48	0,47–0,48
185	0,47–0,50	0,46
240	0,48–0,47	0,43
300	0,47–0,48	0,44-0,45



Kuva B2-2. Kuormitettavuuden muutos putkiasennuksessa eri kosteusarvoilla [Annex C, TKK raportti 1].

Samankaltainen tarkastelu on tehty pienjännitekaapeleiden kuormittamisesta erilaisissa maaperissä [Annex C, TKK raportti 2]. Pienjännitekaapeleiden kuivat olosuhteet ovat vielä tärkeämpiä tarkastella, sillä niiden kuormitusaste on usein paljon suurempi kuin keskijännitekaapeleiden.



Kuva B3-3. Pienjännitekaapelin maa-asennus. Suhteellinen kuormitettavuus eri poikkipinnoilla ja eri ympäristöolosuhteissa, johtimen lämpötila 70 ºC [Annex C, TKK raportti 2].

LIITE B3 Muuntajat

TKK:n raportissa arvioidaan ilmaston muutoksen vaikutuksia jakelu- ja tehomuuntajiin. Raportissa [Annex C, TKK raportti 3] arvioidaan tekijöitä, jotka vaikuttavat muuntajan elinikään. Ilmaston muutoksen suurin vaikutus muuntajan kannalta on lämpötilan nousu. Taulukoissa B3-1 ja B3-2 on laskettu jakelu- ja tehomuuntajien kuormitettavuus ympäristölämpötilan ääriarvoilla.

Taulukko B3-1. Jakelumuuntajan käämityksen suurimman lämpötilan laskelmat äärilämpötilassa (33,8 °C)[Annex C, TKK raportti 3].

Nimellis teho (kVA)	Jännite (kV/kV)	Jäähdytys-tapa	Tyhjä-käynti-häviö (W)	Kuormitus -häviö nimellis-virralla (W)	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H (kun $K = 1$)	K (kun θ_H = 98 °C)
50	20/0,4	ONAN	150	1403	9,3	60,4	21,3	115,5	0,868
100	20/0,4	ONAN	245	1973	8,0	60,3	21,3	115,5	0,867
200	20/0,4	ONAN	465	2743	5,9	60,2	21,3	115,4	0,864
315	20/0,4	ONAN	680	3672	5,4	60,2	21,3	115,4	0,862
500	20/0,4	ONAN	930	5276	5,7	60,2	21,3	115,4	0,863
800	20/0,4	ONAN	1400	6859	4,9	60,2	21,3	115,3	0,861
1000	20/0,4	ONAN	1500	8864	5,9	60,2	21,3	115,4	0,864

Taulukko B3-2. Tehomuuntajan käämityksen suurimman lämpötilan laskelmat äärilämpötilassa 33,8 °C [Annex C, TKK raportti 3].

Käämi-tys	Nimellis-teho (MVA)	Jäähdytystapa	Tyhjä-käynti-häviö (kW)	Kuormitus-häviö nimellis-virralla (kW)	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H	K (kun θ_H = 98°C)
Al	16	ONAN	16,1	92,9	5,8	56,4	25,2	115,4	0,865
Cu	20	ONAN	16,8	111,8	6,6	56,4	25,2	115,5	0,867
Al	25	ONAN	21,8	127,7	5,8	56,4	25,2	115,4	0,865
Cu	31,5	ONAN/ONAF	24,5	143,5	5,8	56,4	25,2	115,4	0,865
Al	40	ONAN/ONAF	33,5	187,8	5,6	56,4	25,2	115,4	0,865

Muuntajan kuormitettavuus on tarkasteltava tapauskohtaisesti. Muuntajakohtaiset häviöt, äärilämpötila ja sen kestoaika, maksimikuormituksen ajankohta ja kesto sekä muuntajan aikavakiot vaikuttavat lopputulokseen.

Projektin osapuolille lähetettyyn kyselyyn vastanneet verkkoyhtiöt käyttävät muuntajan mitoitukseen -40 ºC ja 40 ºC välillä olevia ulkolämpötila-arvoja. Esimerkiksi ulkona olevat jakelumuuntajat mitoitetaan yleisesti -40 ºC mukaan ja sisätiloissa olevat yhtiöstä riippuen 20 ºC, 30 ºC tai 40 ºC. Sähköasemien tehomuuntajat mitoitetaan yleisesti 20 ºC mukaan, mutta ympäristönlämpötilaa -40 ºC on myös käytetty mitoitusperusteena. Maksimikuormitettavuutena on käytetty 80 % sisätilojen jakelumuuntajille ja 130 % pylväsmuuntajille.

Liitteenä olevassa TKK:n raportissa on laskettu kuormitettavuuden aleneminen, kun ympäristön lämpötila on 20 ºC ja 40 °C. Muuntajan kuormitettavuus pienenee tällöin pahimmillaan 20 %. Tämä edellyttää, että huippukuormitus ja pitkä hellejakso osuvat samaan aikaan.

Annex C: Reports of TKK, Helsinki University of Technology

TKK Report 1	Hashmi, G.M., Millar, R.J., Lehtonen, M. Cable ampacity analysis for MV underground networks laid in thermally unstable environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology, 2007. 16 p.
TKK Report 2	Hashmi, G.M., Millar, R.J., Lehtonen, M. Cable ampacity analysis for LV underground networks laid in thermally unstable environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology, 2007. 16 p.
TKK Report 3	Hashmi, G.M., Millar, R.J., Lehtonen, M. Transformers Loading Conditions for Future Thermally Unstable Environments. Espoo. Power Systems and High voltage engineering, Helsinki University of Technology, 2007. 18 p.

Cable Ampacity Analysis for MV Underground Networks Laid in Thermally Unstable Environments

Report for ILMUU2-Project

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1. Introduction

Underground power cables are more expensive to install and maintain than overhead lines. The greater cost of underground installation reflects the high cost of materials, equipment, labour, and time necessary to manufacture and install the cable. The large capital cost investment makes it necessary to use their full capacity. On the other hand, the conductor temperature of a power cable limits its ampacity (maximum allowable temperature). Also, the operating temperature adversely affects the useful working life of a cable. Excessive conductor temperature may irreversibly damage the cable insulation and jacket.

A successful model was proposed for calculating the ampacity of underground cables by Neher-McGrath in 1957 [1]. The Neher-McGrath Model has been widely accepted for over 40 years. Today, the greater majority of utilities and cable manufacturers have been using the IEC-60287 standard [2]. The analytical modeling of the heat transfer mechanism by IEC-60287 works well in simple cable installations. However, the simplifying assumptions and empirical correlations inherent in the analytical method can be significant in complex installations such as crossing cable ducts, cables on trays, cables near buildings, cable splices, etc., thus making solution impossible. The method employs a lot of simplifications and has its limitations. Thus, it is not reliable for the analysis of complex configurations.

Today's computer technology enables the finite element method (FEM); the capability to solve many of these cases with very complex geometrical configuration. It can solve complex installations in any environment and subject to any type of load condition and perform transient analysis efficiently. When the cable surrounding is composed of various materials with different thermal resistivities, the IEC-60287 formulation fails to achieve an acceptable result. Therefore, FEM is also powerful and precise in terms of geometrical modeling complexity. Ampacity analysis of cables with FEM has been studied by many researchers [3, 4, 5].

In this report, current rating calculations for MV power cables in steady-state conditions are performed using an analytical set of thermal equations. The primary goal is to investigate the possible extreme circumstances due to climate change. A fully transient algorithm that generates and utilises governing exponential equations has already developed for this purpose [6], and this report uses a steady-state simplification of that algorithm. The analysis is made for different installation configurations under the various Finnish environmental conditions. The calculated results are confirmed where possible by comparing the results obtained from FEMLAB simulations.

This study is useful for the electric power utilities to revise allowable current ratings to avoid damage to their power cables, as well as for the safe and reliable distribution of power to the customers.

2. Factors affecting the thermal resistivity of soils

An evaluation of the thermal properties of the soils that surround underground transmission and distribution lines is an important part of the existing design procedures for underground power cables. The permissible current in underground power cables depends on the maximum allowable temperature of the cable insulation material. Because heat is generated by underground cables, assessment of the thermal conductivity (or thermal resistivity) of the soil surrounding the cable is critical to avoid failure of the cables by overheating and to achieve the highest possible current loading. Soils with higher thermal resistance will not dissipate heat as rapidly away from cables as soils with a low thermal resistance [7].

The thermal resistivity of a soil is primarily influenced by the following parameters:

2.1. Soil composition

Soil is a three–phase medium composed of solid materials (inorganic/and organic), liquid (water), and gases (air). Heat flowing through soil must flow through the solid mineral grains and the medium in which they are embedded in a complex system of series and parallel paths, therefore, the thermal resistivity of the soil depends on the thermal resistivity of its components materials and the soil structure. As the resistivities of most minerals are significantly less than that of water and air, therefore, the soil mass should consist of solids if low resistivity is required.

2.2. Density

One of the most important influences on the thermal resistivity of the soil is density. The presence of air with its high thermal resistivity greatly increases the overall thermal resistivity of the soil as compared with its soil components [7]. Thus, by reducing the total void volume and improving the contact between the solid grains through densification of the soil mass, a reduction in the thermal resistivity of the material will be achieved. The density of soils may be changed by artificial means such as compaction or disturbance of in-situ soils (e.g., during cable installation) and by such natural factors as consolidation, shrinkage, or swelling.

2.3. Moisture content

Another factor to be considered for the thermal resistivity of the soil is to what extent the voids (or pore spaces) are filled with water. The terms usually used to characterize this soil property are moisture content and degree of saturation. The moisture content is defined as the mass of free water expressed as a percentage of the dry mass of a given soil volume while the degree of saturation is defined as the volume of free water expressed as a percentage of the volume of voids.

The importance of the soil moisture is illustrated in Fig. 1. As moisture is added to the soil as a thin film around the soil particles, a path for the flow of heat which which bridges the air gap between the solid particles is provided. By increasing the effective contact area between particles, these films greatly reduce the thermal resistivity of the soil. This trend is observed in Fig. 1 [7].

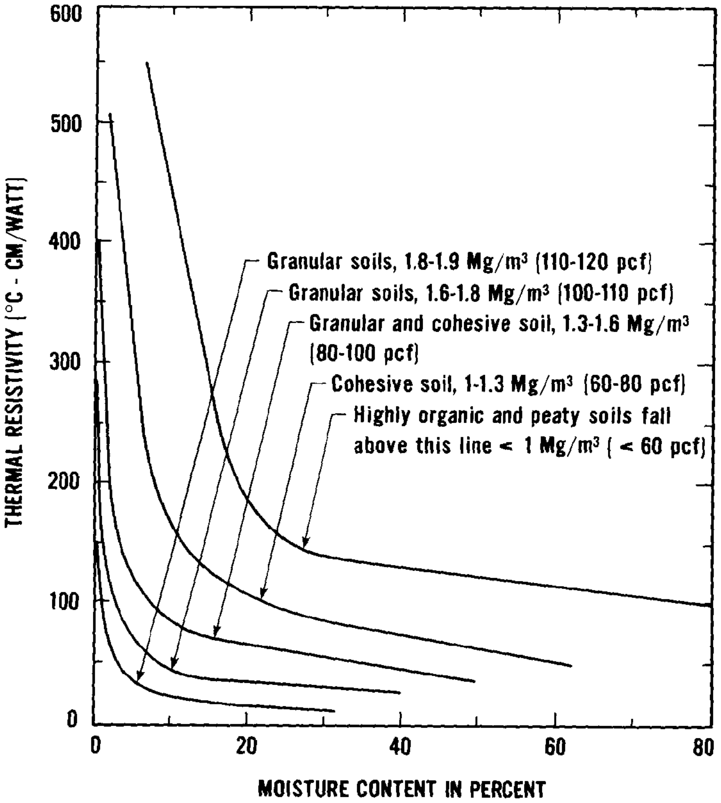

Fig. 1: The effect of moisture content and dry density on the thermal resistivity of soils

3. Installation configurations

The AHXAMK-W 3-core 20 kV cable [8] is used in this study. The cable is buried at a depth of 0.7 m. MV cables buried in the following two ways have been considered for ampacity (current rating and thermal capacity) calculations.

i. Direct burial
ii. Tube installation

4. Various installation environmental conditions

The value of thermal resistivity usually used for cable rating is 1.0 Km/W. This value seems suitable for most HV installations with a well controlled installation environment, but not necessarily for all MV installations. Due to dried soil, material near MV cables sometimes has a thermal resistivity as high as 5.0 Km/W. The critical temperature rise (of the cable surface over ambient) for moisture migration is generally assumed to be 35°C, however, it has been observed that moisture migration begins from as low as 10°C above ambient in sand backfills [9]. If such locations dry out due to high temperatures in the cables or other services, or due to a long-term dry period, such as the summers of 2002, 2003, and 2006, cable temperatures may run hotter than expected and leave little margin to cope with emergency peaks in loading. The following various environmental conditions have been investigated in this report to demonstrate their effects on the cable current rating.

a) No moisture migration (moist environment)
b) Moisture migration in controlled environment
c) Moisture migration in uncontrolled environment
d) Fully dry environment (worst case)

In the controlled environment, the cable is installed in backfill (usually sand or crushed stone) with known properties, where as in the uncontrolled case, the installation is in native soil, which in the worst case may be fully dried out due to a long-term dry period and the effect of vegetation[1]. The flowing table gives a brief description of each of the above environmental conditions in terms of its ambient temperature, soil resistivity (ρ_s), and dry soil resistivity (ρ_{dry}):

Table 1: Various environmental parameters

Sr. No.	Environmental condition	Ambient temperature (°C)	ρ_s (Km/W)	ρ_{dry} (Km/W)
1	a	20	1.2	-
2	b	20	1.2	2.5
3	c	20	1.2	5
4	d	20	5	-

5. Ampacity calculations for different installations

The ampacity calculations (current rating and thermal capacity) for direct burial and tube installations under various environmental conditions have been made in this section using an algorithm based on analytical equations [6]. In essence, the algorithm is simple and computationally light. The algorithm is run in Mathcad®.

The calculations are performed for different cross-sections of the conductors. The conductor data for different cross-sections is collected from the cable manufacturer's data

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[1] It has been observed that vegetation like trees are able to absorb practically all moisture in an area close to their roots. This observation should affect the way of installation and maintenance in cases where the cable is laid directly in the native soil.

sheet [8]. The allowable temperature limits are 65°C and 90°C as given in the data sheet. The nominal current rating for a given temperature is taken from the data sheet. The per unit (P.U) current ratings are obtained by dividing the calculated current ratings by the nominal current ratings. The following tables (Table 2-7) illustrate the calculated ampacity data for different installations. Some values are replaced by a subscript UD (un-determined) where the calculated temperature is more than 1000°C, showing an unrealistic situation.

5.1. Direct burial calculations

Table 2: Effect of moisture migration on current rating in controlled environment

Sr. No.	**Cross sectional area (mm^2)**	**Direct burial without moisture migration** $\rho_s = 1.2$				**Direct burial with moisture migration in controlled environment** $\rho_s = 1.2/2.5$			
		P.U current rating at		**Conductor temp. at rated load designed @**		**P.U current rating at**		**Conductor temp. at rated load designed @**	
		65°C	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**
1	**70**	0.85	0.87	86	121	0.77	0.74	139	252
2	**95**	0.87	0.87	83	120	0.78	0.74	133	251
3	**120**	0.87	0.86	82	126	0.78	0.72	132	278
4	**150**	0.86	0.84	84	132	0.77	0.70	138	305
5	**185**	0.89	0.83	80	137	0.79	0.67	127	328
6	**240**	0.88	0.80	81	150	0.78	0.66	132	392
7	**300**	0.87	0.80	82	143	0.77	0.67	133	356

Table 3: Effect of moisture migration on current rating in uncontrolled environment

Sr. No.	**Cross sectional area (mm^2)**	**Direct burial without moisture migration** $\rho_s = 1.2$				**Direct burial with moisture migration in uncontrolled environment** $\rho_s = 1.2/5$			
		P.U current rating at		**Conductor temp. at rated load designed @**		**P.U current rating at**		**Conductor temp. at rated load designed @**	
		65°C	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**
1	**70**	0.85	0.87	86	121	0.71	0.65	422	UD
2	**95**	0.87	0.87	83	120	0.72	0.65	380	UD
3	**120**	0.87	0.86	82	126	0.72	0.63	372	UD
4	**150**	0.86	0.84	84	132	0.71	0.62	418	UD
5	**185**	0.89	0.83	80	137	0.73	0.6	347	UD
6	**240**	0.88	0.80	81	150	0.72	0.59	377	UD
7	**300**	0.87	0.80	82	143	0.71	0.59	371	UD

Table 4: Effect of moisture migration on current rating in fully dry environment

Sr. No.	Cross sectional area (mm^2)	Direct burial without moisture migration $\rho_s = 5$				Direct burial with moisture migration in worst environment $\rho_s = 5/5$			
		P.U current rating at		Conductor temp. at rated load designed @		P.U current rating at		Conductor temp. at rated load designed @	
		65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C
1	**70**	0.46	0.47	642	UD	0.46	0.47	642	UD
2	**95**	0.46	0.47	584	UD	0.46	0.47	584	UD
3	**120**	0.47	0.46	572	UD	0.47	0.46	572	UD
4	**150**	0.46	0.44	633	UD	0.46	0.44	633	UD
5	**185**	0.47	0.44	536	UD	0.47	0.44	536	UD
6	**240**	0.46	0.42	560	UD	0.46	0.42	560	UD
7	**300**	0.46	0.42	563	UD	0.46	0.42	563	UD

5.2. Tube Installation

Table 5: Effect of moisture migration on current rating in controlled environment

Sr. No.	Cross sectional area (mm^2)	Tube installation without moisture migration $\rho_s = 1.2$				Tube installation with moisture migration in controlled environment $\rho_s = 1.2/2.5$			
		P.U current rating at		Conductor temp. at rated load designed @		P.U current rating at		Conductor temp. at rated load designed @	
		65°C	90°C	65°C	90°C	65°C	90°C	65°C	90°C
1	**70**	0.74	0.77	109	155	0.75	0.73	140	236
2	**95**	0.76	0.77	105	154	0.76	0.72	135	240
3	**120**	0.76	0.76	104	163	0.76	0.70	135	267
4	**150**	0.75	0.74	107	170	0.75	0.69	141	288
5	**185**	0.77	0.73	102	177	0.77	0.68	131	314
6	**240**	0.76	0.70	103	195	0.76	0.65	136	379
7	**300**	0.76	0.71	104	187	0.75	0.66	140	371

Table 6: Effect of moisture migration on current rating in uncontrolled environment

Sr. No.	**Cross sectional area (mm^2)**	**Tube installation without moisture migration** $\rho_s = 1.2$				**Tube installation with moisture migration in uncontrolled environment** $\rho_s = 1.2/5$			
		P.U current rating at		**Conductor temp. at rated load designed @**		**P.U current rating at**		**Conductor temp. at rated load designed @**	
		65°C	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**
1	**70**	0.74	0.77	109	155	0.75	0.67	251	773
2	**95**	0.76	0.77	105	154	0.76	0.68	247	887
3	**120**	0.76	0.76	104	163	0.76	0.66	244	UD
4	**150**	0.75	0.74	107	170	0.75	0.65	270	UD
5	**185**	0.77	0.73	102	177	0.76	0.63	248	UD
6	**240**	0.76	0.70	103	195	0.74	0.60	284	UD
7	**300**	0.76	0.71	104	187	0.74	0.60	283	UD

Table 7: Effect of moisture migration on current rating in fully dry environment

Sr. No.	**Cross sectional area (mm^2)**	**Tube installation without moisture migration** $\rho_s = 5$				**Tube installation with moisture migration in worst environment** $\rho_s = 5/5$			
		P.U current rating at		**Conductor temp. at rated load designed @**		**P.U current rating at**		**Conductor temp. at rated load designed @**	
		65°C	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**	**65°C**	**90°C**
1	**70**	0.48	0.5	392	UD	0.49	0.5	390	UD
2	**95**	0.49	0.49	383	UD	0.49	0.5	380	UD
3	**120**	0.49	0.48	382	UD	0.49	0.48	378	UD
4	**150**	0.48	0.47	415	UD	0.48	0.48	409	UD
5	**185**	0.47	0.46	379	UD	0.5	0.46	372	UD
6	**240**	0.48	0.43	406	UD	0.47	0.43	443	UD
7	**300**	0.47	0.44	423	UD	0.48	0.45	412	UD

6. Results and discussion

The calculated data given in previous section is plotted for different installations under various environmental conditions and the plots are given below:

6.1. Results for direct burial

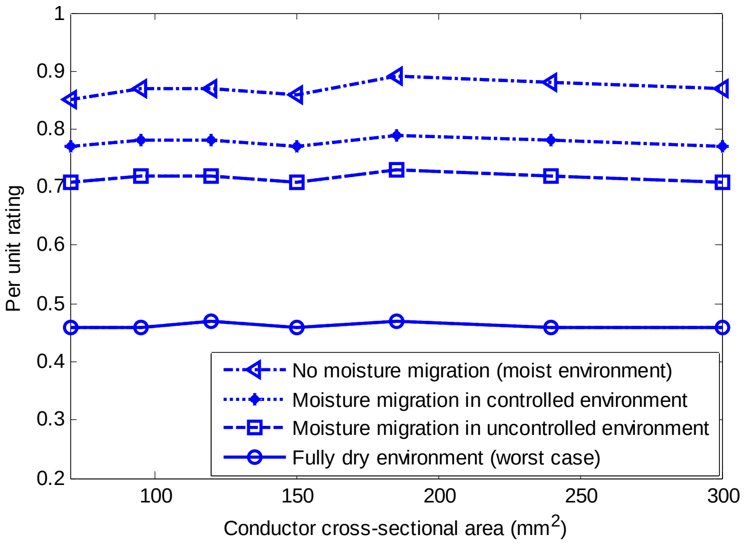

Fig. 2: Per unit current ratings under various environmental conditions for different cross-sections of conductor at 65°C temperature

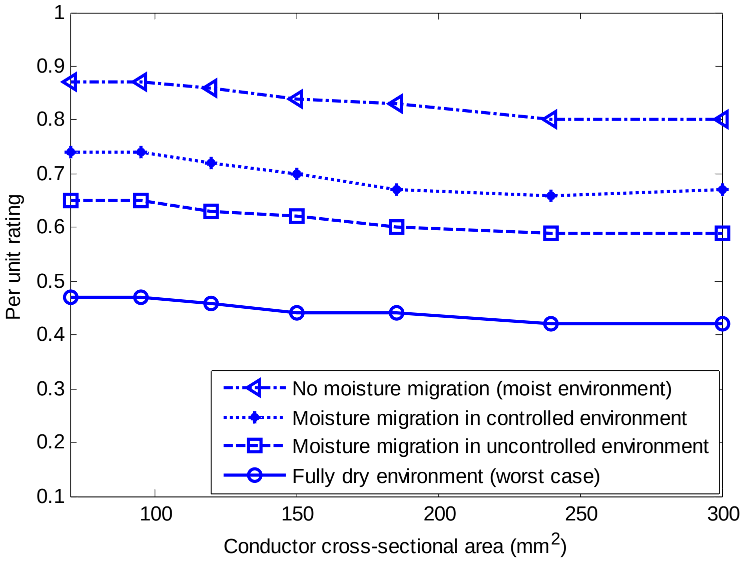

Fig. 3: Per unit current ratings under various environmental conditions for different cross-sections of conductor at 90°C temperature

It is revealed from Figures 2 and 3 that for the same temperature rise, the current rating of the conductor tends to decrease as the moisture contents decrease. In other words, the conductor operating at the rated capacity must have higher temperature than the permissible limit.

6.2. Results for tube installation

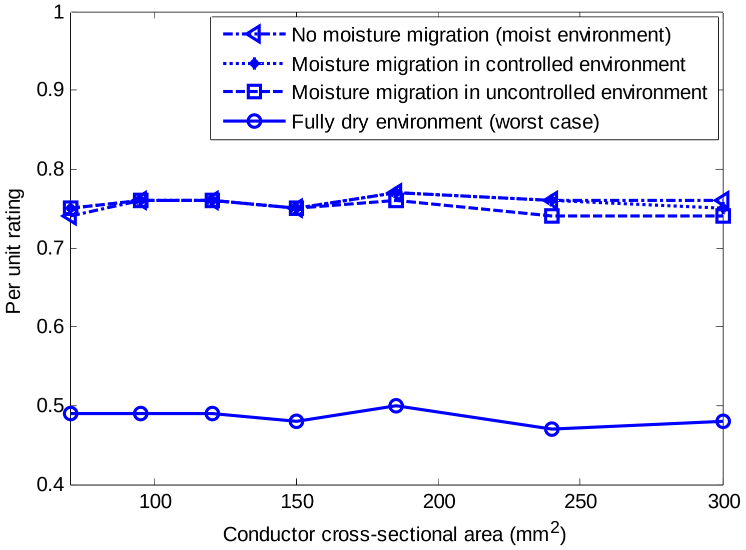

Fig. 4: Per unit current ratings under various environmental conditions for different cross-section of conductor at 65°C temperature

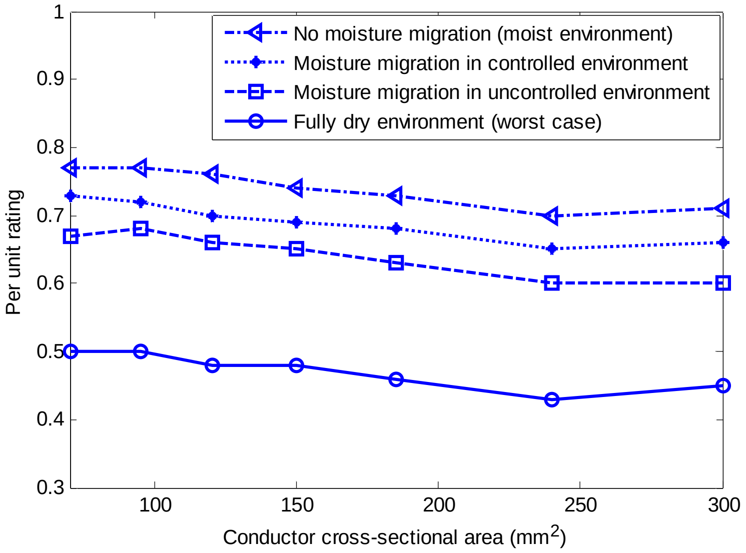

Fig. 5: Per unit current ratings under various environmental conditions for different cross-section of conductor at 90°C temperature

It can be concluded from Figures 4 and 5 that for the same temperature rise, the current rating of the conductor tends to decrease as the moisture contents decrease. In other words, a conductor operating at the rated capacity must have a higher temperature than the permissible limit. It is also clear that moisture contents do not have a significant effect on the conductor current rating in the case of tube installation (specifically for a 65°C permissible temperature limit). However, significant effect can be seen for the fully dry (worst case) environment.

6.3. Direct burial v/s tube installation

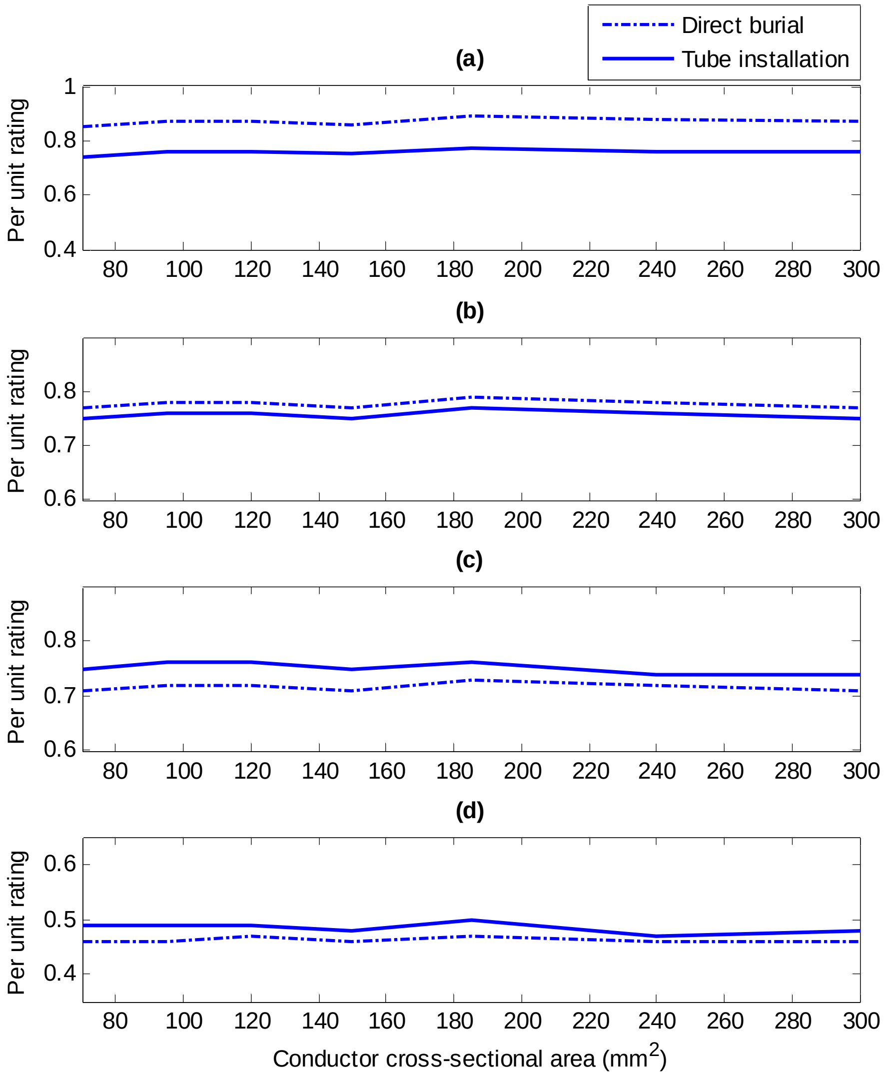

Fig. 6: Direct burial v/s tube installation for conductor at 65°C temperature in (a) no moisture migration (moist environment), (b) moisture migration in controlled environment, (c) moisture migration in uncontrolled environment, (d) fully dry environment (worst case).

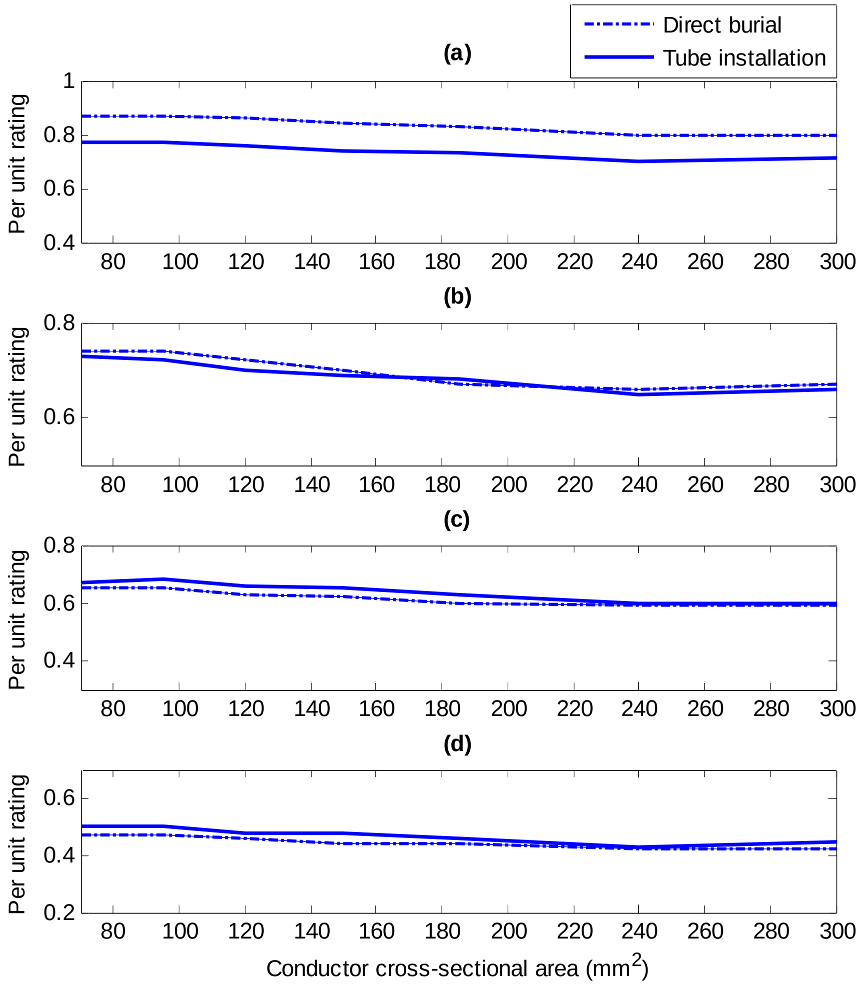

Fig. 7: Direct burial v/s tube installation for conductor at 90°C temperature in (a) no moisture migration (moist environment), (b) moisture migration in controlled environment, (c) moisture migration in uncontrolled environment, (d) fully dry environment (worst case).

From the above Figures 6 and 7, in case of (a) and (b), the direct burial installation has higher current ratings, however, in case of (c) and (d), the tube installation has higher current ratings. Therefore, it is suggested that tube installation should be preferred in case of the Finnish uncontrolled environment (native peaty soil installation).

6.3.1. Comparison for minimum and maximum conductor cross-sections

The conductor data used in this analysis has been taken from the available data sheet [8]. In the data sheet, the conductor has a minimum cross-sectional area of 70mm^2 and maximum of 240 mm^2. It would be interesting to investigate the minimum and maximum cross-sections of the conductor for cable ampacity analysis. Therefore, a comparative study for direct burial and tube installation has been carried out for minimum and maximum cross section areas as given below.

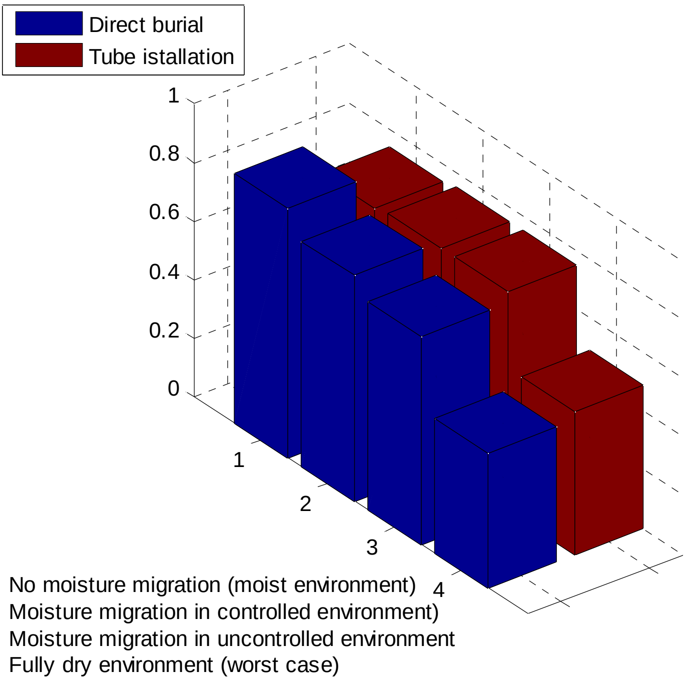

Fig 8: Direct burial v/s tube installation under various environmental conditions for conductor at 65°C temperature having minimum cross- sectional area of 70 mm^2

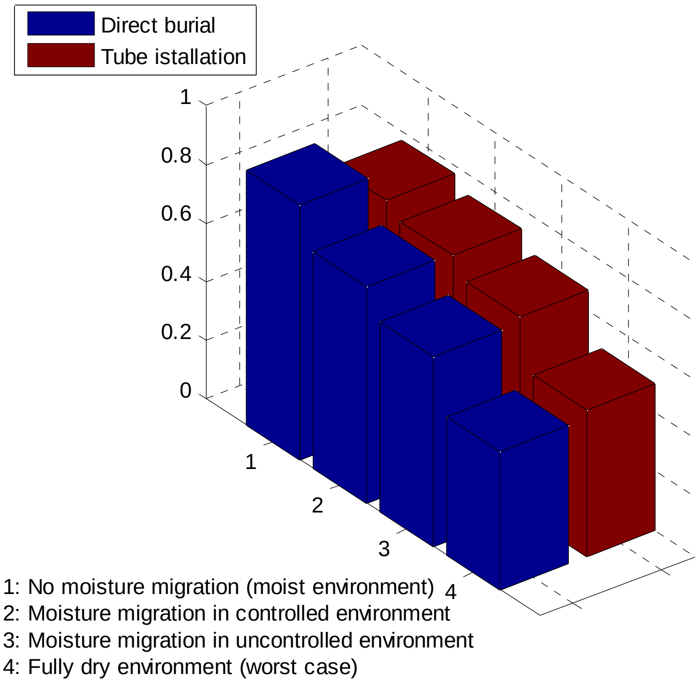

Fig 9: Direct burial v/s tube installation under various environmental conditions for conductor at 90°C temperature having minimum cross- sectional area of 70 mm^2

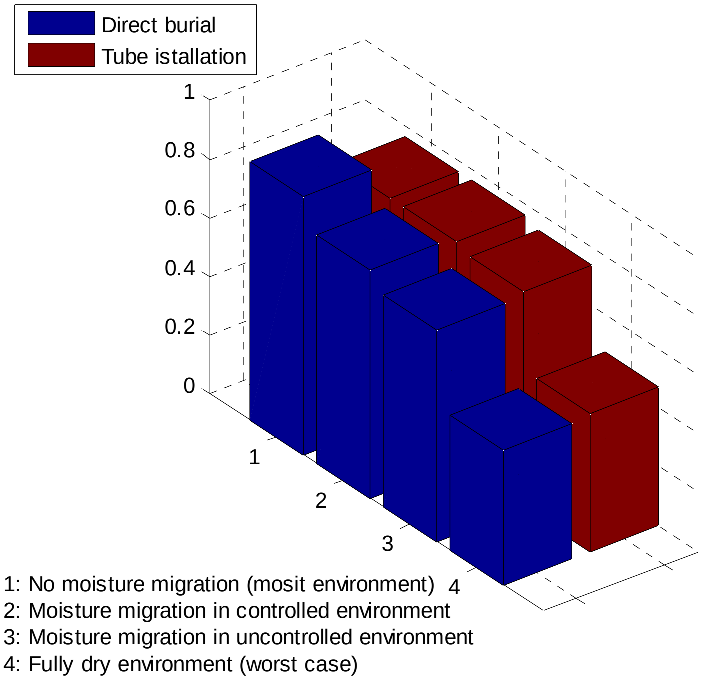

Fig 10: Direct burial v/s tube installation under various environmental conditions for conductor at 65°C temperature having minimum cross- sectional area of 240 mm^2

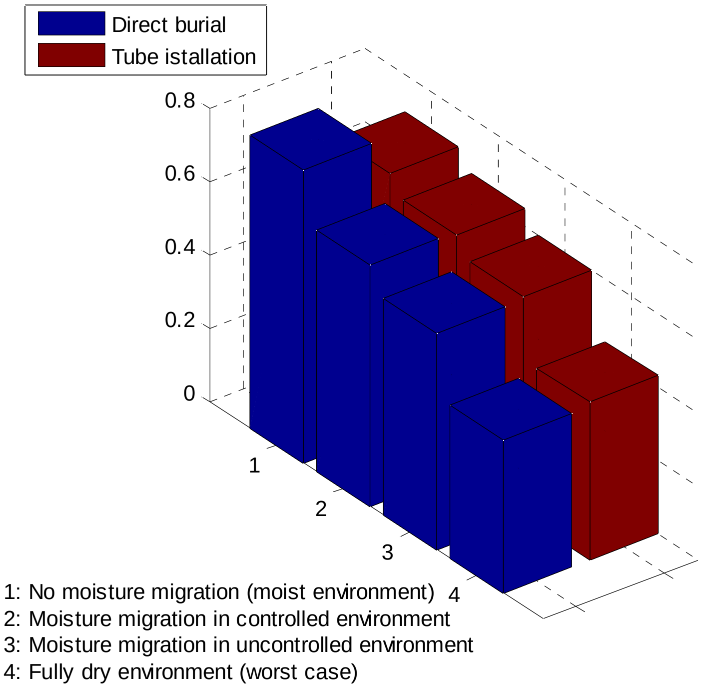

Fig 11: Direct burial v/s tube installation under various environmental conditions for conductor at 90°C temperature having minimum cross- sectional area of 240 mm^2

It is revealed from above figures that under the permissible limits of temperature rise, the conductor current rating is higher in the case of direct burial installation for the first two environmental conditions (1 and 2), however, the conductor current rating is higher in case of tube installation for the other two environmental cases (3 and 4). The current rating pattern does not change under the different environmental conditions for minimum or maximum conductor cross-sectional area, which proves the applicability of this technique to determine current rating for any size of conductor.

7. Conclusions

- A novel analytical formulation for the calculation of current rating/thermal capacity under various environmental conditions has been presented. The results are to a large extent confirmed by comparing with those obtained from FEMLAB.

- As the moisture contents decrease due to the moisture migration phenomenon occurring in the vicinity of a cable, the current rating of the conductor also decreases for the same permissible thermal limits. Therefore, it is suggested to load the cables at lower current ratings than those given in the specifications for safe and reliable operation.

- In the case of direct burial or tube installation, the current rating decreases due to moisture migration, however, the effect is more significant in case of direct burial installation.

- Slightly higher current ratings are obtained in the case of tube installation for Finnish uncontrolled environment (but note, these ratings are substantially lower than the catalogue values!)

- The pattern of decreasing current rating due to moisture migration under various environmental conditions is the same for minimum or maximum conductor cross-sectional area, which proves the applicability of this technique for any size of conductor.

- In the worst case, fully dried out peaty native soil; the load capacity of the cables is reduced to less than 50% of the normal rating. This scenario is possible during a long-term dry period, especially if there is vegetation close to the cable route.

8. References

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Cable Ampacity Analysis for LV Underground Networks Laid in Thermally Unstable Environments

Report for ILMUU2-Project

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1. Introduction

Underground power cables are more expensive to install and maintain than overhead lines. The greater cost of underground installation reflects the high cost of materials, equipment, labour, and time necessary to manufacture and install the cable. The large capital cost investment makes it necessary to use their full capacity. On the other hand, the conductor temperature of a power cable limits its ampacity (maximum allowable current). Also, the operating temperature adversely affects the useful working life of a cable. Excessive conductor temperature may irreversibly damage the cable insulation and jacket.

A successful model was proposed for calculating the ampacity of underground cables by Neher-McGrath in 1957 [1]. The Neher-McGrath Model has been widely accepted for over 40 years. Today, the greater majority of utilities and cable manufacturers have been using the IEC-60287 standard [2]. The analytical modeling of the heat transfer mechanism by IEC-60287 works well in simple cable installations. However, the simplifying assumptions and empirical correlations inherent in the analytical method make solution difficult for installations such as crossing cable ducts, cables on trays, cables near buildings, cable splices, etc. Thus, the standards are not directly applicable for the analysis of complex configurations.

Today's computer technology enables the finite element method (FEM) the capability to solve many of these cases with very complex geometrical configurations. It can solve complex installations in just about any environment and subject to any type of load condition, and can perform transient analysis efficiently. When the cable surrounding is composed of various materials with different thermal resistivities, the IEC-60287 formulation fails to achieve an acceptable result. Ampacity analysis of cables with FEM has been studied by many researchers [3-5]; however, it becomes tedious to draw a multitude of different models for varying specifications.

This report deals with current rating calculations performed for 3-phase low voltage (LV) cross linked polyethylene (XLPE) power cable installations (consisting of 4 conductors) in steady-state conditions using an analytical set of thermal equations. The primary goal is to investigate the possible extreme circumstances due to climate change. A fully transient algorithm that generates and utilizes governing exponential equations has already been developed for this purpose [6], and this report uses a steady-state simplification of that algorithm. The analysis is made for different installation configurations under the various Finnish environmental conditions. The calculated results are confirmed where possible by comparing the results obtained from FEMLAB simulations

This study will be useful for the electric power utilities to revise allowable current ratings to avoid damage to their power cables, as well as for the safe and reliable distribution of power to the customers.

2. Factors affecting the thermal resistivity of soils

An evaluation of the thermal properties of the soils that surround underground transmission and distribution lines is an important part of the existing design procedures for underground power cables. The permissible current in underground power cables depends on the maximum allowable temperature of the cable insulation material. Because heat is generated by underground cables, assessment of the thermal conductivity (or its reciprocal, the thermal resistivity) of the soil surrounding the cable is critical to avoid failure of the cables by overheating and to achieve the highest possible current loading. Soils with higher thermal resistance will not dissipate heat as rapidly away from cables as soils with a low thermal resistance [7].

The thermal resistivity of a soil is primarily influenced by the following parameters:

2.1. Soil composition

Soil is a three-phase medium composed of solid materials (inorganic/and organic), liquid (water), and gases (air). Heat flowing through soil must flow through the solid mineral grains and the medium in which they are embedded in a complex system of series and parallel paths, therefore, the thermal resistivity of the soil depends on the thermal resistivity of its components materials and the soil structure. As the resistivities of most minerals are significantly less than that of water and air, therefore, the soil mass should consist of solids if low resistivity is required.

2.2. Density

One of the most important influences on the thermal resistivity of the soil is density. The presence of air with its high thermal resistivity greatly increases the overall thermal resistivity of the soil as compared with its soil components [7]. Thus, by reducing the total void volume and improving the contact between the solid grains through densification of the soil mass, a reduction in the thermal resistivity of the material will be achieved. The density of soils may be changed by artificial means such as compaction or disturbance of in-situ soils (e.g., during cable installation) and by such natural factors as consolidation, shrinkage, or swelling.

2.3. Moisture content

Another factor to be considered for the thermal resistivity of the soil is to what extent the voids (or pore spaces) are filled with water. The terms usually used to characterize this soil property are moisture content and degree of saturation. The moisture content is defined as the mass of free water expressed as a percentage of the dry mass of a given soil volume while the degree of saturation is defined as the volume of free water expressed as a percentage of the volume of voids.

The importance of the soil moisture is illustrated in Fig. 1. As moisture is added to the soil as a thin film around the soil particles, a path for the flow of heat which which bridges the air gap between the solid particles is provided. By increasing the effective contact area between particles, these films greatly reduce the thermal resistivity of the soil. This trend is observed in Fig. 1 [7].

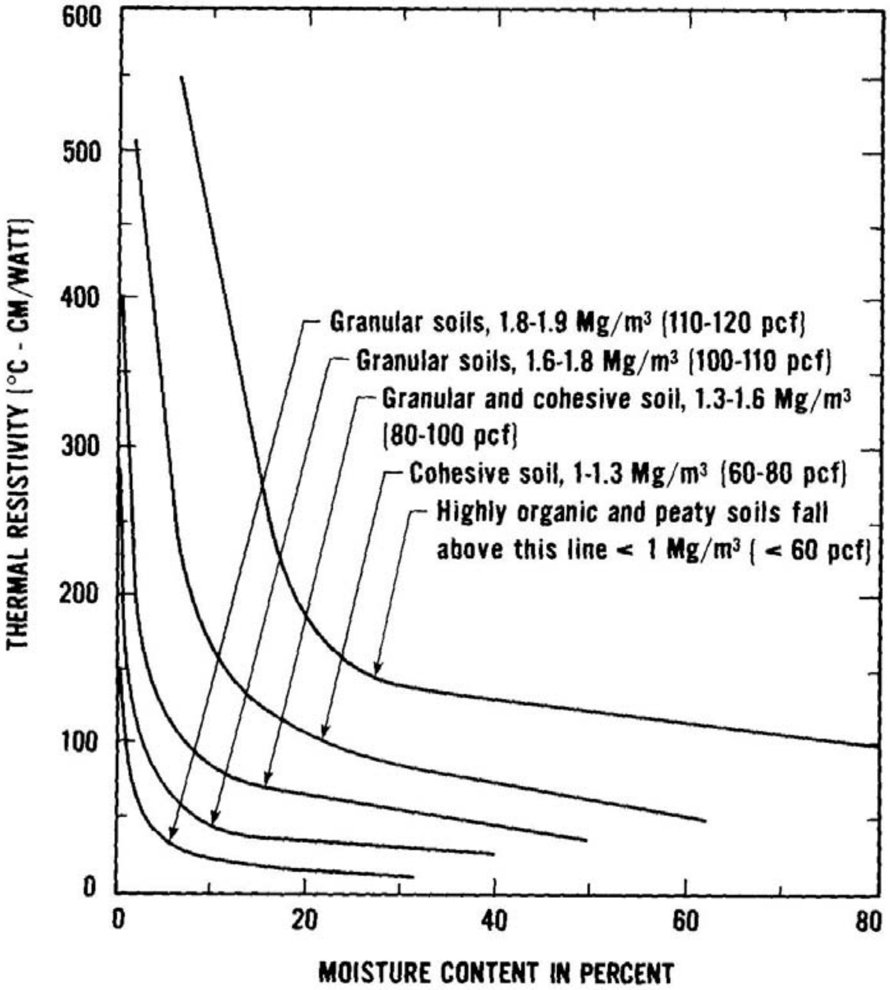

Fig. 1: The effect of moisture content and dry density on the thermal resistivity of soils

What is more, the tendency for moisture to migrate away from a heat source, known as moisture migration, will occur at lower temperatures when the nominal moisture content of a given porous material is lower. This will be discussed in section 4, and is of particular significance when LV cables are directly buried.

3. Different cable Installations

The AXMK 4-core 1 kV power cable with XLPE insulated aluminum conductors is used in this study [8]. The LV cables buried in the following two ways have been considered for ampacity and thermal capacity calculations.

3.1. Direct burial

The most common method for installing power cables underground is to lay them directly in the soil at a certain depth. In this report, 3-phase AXMK cables are considered, which consist of 4 conductors contained within the same jacket. For ampacity calculations, the cable under investigation is assumed to be buried at a depth of 0.7 m in different environments. The report, to keep within some bounds, assumes there is only one cable in the same thermal environment, but in reality, several cables may be installed close to each other, and even in the same trench as MV cables. In such installations, further derating is required.

3.2. Tube installation

In this arrangement, the cable is laid inside a plastic tube that is often of a corrugated construction to provide a good compromise between mechanical stiffness and light weight. The installation tube is given outside/inside diameters of 75/63 mm for the smaller cables (up to 4G95) and 110/94 mm for the larger cables, with 2mm wall thickness on either side of the air cavities in the corrugated section. The air interface, and to some extent the heat transfer across the composite section of the tube is still quite challenging to model accurately, being a rather difficult to solve combination of radiation, convection, and conduction [6]. It is assumed that there is only one cable inside the tube, but some rough guidelines are given with regard to derating multi-cable installations.

4. Various installation environmental conditions

The value of thermal resistivity usually used for cable rating is 1 Km/W. This value seems suitable for most high voltage (HV) installations with a well controlled installation environment, but not necessarily for all medium voltage (MV) or LV installations. Due to dried soil, material near MV or LV cables sometimes has a thermal resistivity as high as 5 Km/W. The critical temperature rise (of the cable surface over ambient) for moisture migration is generally assumed to be 35°C, however, it has been observed that moisture migration can begin from as low as 10°C above ambient in sand backfills [9]. If such locations dry out due to high temperatures in the cables or other services, or due to a long-term dry period (such as the dry summers that occurred in Finland in 2002, 2003, and 2006), cable temperatures may run hotter than expected and leave little margin to cope with emergency peaks in loading. The following environmental conditions have been investigated in this paper to demonstrate their effects on the cable current rating:

a) No moisture migration (moist environment);
b) Moisture migration in controlled environment;
c) Moisture migration in uncontrolled environment; and
d) Fully dry environment (worst case)

In the controlled environment, the cable is installed in backfill (usually sand or crushed stone) with known properties, where as in the uncontrolled case, the installation is in native Finnish soil, which is a highly organic and peaty soil having a dry density of less than 960 kg/m^3. The thermal resistivity of these kinds of soils can be more than 5 Km/W if the moisture contents are only 10-15% [7]. Low moisture content also makes the environment more susceptible to moisture migration. The native soil in the worst case may be fully dried out due to a long-term dry period and the effect of vegetation[1]. Tab. 1 gives a brief description of each of the above mentioned environmental conditions in terms of its ambient temperature, soil resistivity ρ_s, and dry soil resistivity ρ_{dry}.

Table 1. The various environmental parameters

Environmental condition	**Ambient temperature (°C)**	ρ_s **(Km/W)**	ρ_{dry} **(Km/W)**
a	20	1.2	-
b	20	1.2	2.5
c	20	1.2	5
d	20	5	-

5. Cable ampacity calculations

The cable ampacity calculations (determination of the tolerable load current for a given conductor temperature and vice versa) for different installations under various environmental conditions have been made using an algorithm based on analytical equations [6]. The algorithm is based on analytical methods developed in [6], which enable moisture migration modeling, even from tube installations. The tube modeling itself is largely based on methods developed by Neher and McGrath [1]. The algorithm is run in Mathcad®.

The calculations are performed for different cross-sections of the conductor. The conductor data for different cross-sections is collected from the cable manufacturer's data sheet [8]. The allowable temperature limits are 70°C in the data sheet. The nominal current rating for a given temperature is taken from the data sheet. 90°C ratings are only recommended for installations in air, because the heat transfer in air (mainly convection and radiation) improves at higher temperatures. Unfortunately, the opposite is true in buried installations. Our algorithms take moisture migration into account, however, meaning that 90°C ratings can in principle be entertained for buried installations. In this report, however, the per unit (PU) current ratings are obtained by dividing the calculated current ratings by the nominal current ratings. PU rating are only calculated for permissible temperature of 70°C (quite sensibly, nominal current ratings at 90°C for underground cables are not given in the data sheet). The thermal resistances of the conductor have been calculated for the given current ratings in the data sheet in order to "reverse-engineer" the thermal properties of the cables themselves, as accurate construction data and dimensions are not available. The following Tabs. (Tabs. 2-5) illustrate the calculated ampacity data for different cable installations under various

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[1] It has been observed that vegetation like trees are able to absorb practically all moisture in an area close to their roots. This observation should affect the way of installation and maintenance in cases where the cable is laid directly in the native soil.

environmental conditions. Some values are replaced by a subscript UD (un-determined) where the calculated temperature is more than 1000 °C, showing an unrealistic situation. Temperatures of greater than 130 °C can be considered fatal for cables, and the algorithm is not really valid for extremely high temperatures anyway. For example, the linearisation of conductor resistance is generated to be accurate for reasonable temperatures.

In direct burial calculations, the effect of moisture migration can be clearly seen in terms of its lower current loadings at given temperatures or higher temperatures at given rated current loadings (see Tabs. 2 and 3). However, in the tube installation calculations, the effect of moisture migration is not evident in either the controlled or uncontrolled environments, but it most definitely is in the direct burial case (see Tabs. 4 and 5). The PU values of current ratings for tube installation are same for the first three environmental conditions (a, b, and c) because no moisture migration has been detected in these conditions due to the effect of tube installation. This is because a significant proportion of the cable temperature rise occurs across the cable-tube air gap, meaning the surface of the tube itself is not high enough to cause moisture migration according the parameters we have used in this report.

Table 2. Ampacity calculations for direct burial without moisture migration and with moisture migration in controlled environment

Cross sectional area (mm^2)	**Direct burial without moisture migration (moist environment), ρ_s=1.2 Km/W**		**Direct burial with moisture migration in controlled environment, ρ_s/ρ_{dry}=1.2/2.5 Km/W**	
	PU current rating	**Conductor temperature at rated load (^{o}C)**	**PU current rating**	**Conductor temperature at rated load (^{o}C)**
	70^{o}C	**70^{o}C**	**70^{o}C**	**70^{o}C**
16	0.9	84	0.83	120
25	0.88	88	0.82	127
35	0.84	98	0.77	151
50	0.81	104	0.75	163
70	0.80	110	0.74	175
95	0.78	113	0.74	178
120	0.76	120	0.72	195
150	0.74	127	0.70	211
185	0.73	132	0.70	219
240	0.74	130	0.70	208
300	0.72	138	0.69	226

Table 3. Ampacity calculations for direct burial with moisture migration in uncontrolled environment and in fully dry environment

Cross sectional area (mm^2)	**Direct burial with moisture migration in uncontrolled environment, ρ_s/ρ_{dry}=1.2/5 Km/W**		**Direct burial with moisture migration in fully dry environment, ρ_s=5 Km/W**	
	PU current rating	**Conductor temperature at rated load (^{o}C)**	**PU current rating**	**Conductor temperature at rated load (^{o}C)**
	70^{o}C	**70^{o}C**	**70^{o}C**	**70^{o}C**
16	0.78	266	0.52	435
25	0.78	296	0.51	475
35	0.73	423	0.48	645
50	0.72	493	0.47	740
70	0.70	574	0.47	848
95	0.70	579	0.47	856
120	0.71	720	0.46	UD
150	0.67	888	0.45	UD
185	0.67	963	0.44	UD
240	0.68	773	0.45	UD
300	0.67	964	0.44	UD

Table 4. Ampacity calculations for tube installation without moisture migration and with moisture migration in controlled environment

Cross sectional area (mm^2)	**Tube installation without moisture migration (moist environment), ρ_s=1.2 Km/W**		**Tube installation with moisture migration in controlled environment, ρ_s/ρ_{dry}=1.2/2.5 Km/W**	
	PU current rating	**Conductor temperature at rated load (°C)**	**PU current rating**	**Conductor temperature at rated load (°C)**
	70°C	**70°C**	**70°C**	**70°C**
16	0.75	118	0.75	138
25	0.74	121	0.74	145
35	0.71	135	0.71	170
50	0.70	140	0.70	182
70	0.70	145	0.70	194
95	0.69	146	0.69	197
120	0.68	151	0.68	197
150	0.66	158	0.66	213
185	0.66	162	0.66	222
240	0.67	157	0.67	214
300	0.66	166	0.66	233

Table 5. Ampacity calculations for tube installation with moisture migration in uncontrolled environment and in fully dry environment

Cross sectional area (mm^2)	**Tube installation with moisture migration in uncontrolled environment, ρ_s/ρ_{dry}=1.2/5 Km/W**		**Tube installation with moisture migration in fully dry environment, ρ_s=5 Km/W**	
	PU current rating	**Conductor temperature at rated load (°C)**	**PU current rating**	**Conductor temperature at rated load (°C)**
	70°C	**70°C**	**70°C**	**70°C**
16	0.75	202	0.53	326
25	0.74	221	0.52	351
35	0.71	293	0.49	441
50	0.70	341	0.48	505
70	0.70	392	0.47	573
95	0.69	416	0.47	606
120	0.68	385	0.47	563
150	0.66	455	0.46	654
185	0.66	506	0.46	723
240	0.67	478	0.46	670
300	0.66	584	0.45	828

6. Results and discussion

The results drawn for the direct burial and tube installations under various environmental conditions at different permissible temperatures using the calculated data given in the previous section are shown in Figures 2 and 3, respectively.

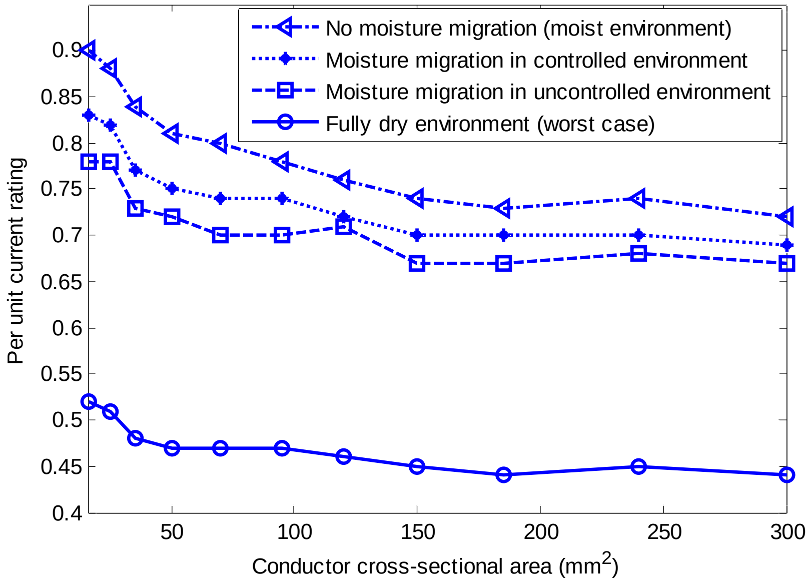

Fig. 2. PU current ratings for direct burial under various environmental conditions for different cross-sections of conductor at 70°C

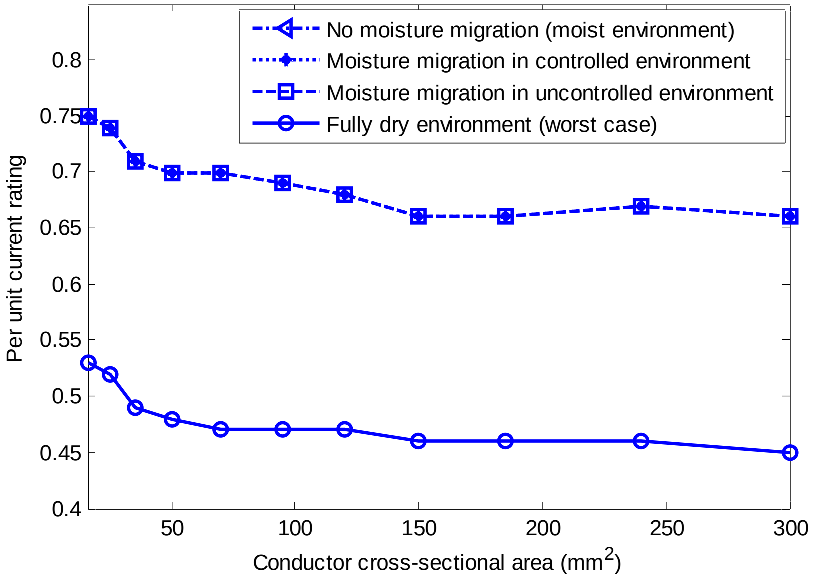

Fig. 3. PU current ratings for tube installation under various environmental conditions for different cross-sections of conductor at 70°C

It is revealed from Figure 2 that for the same temperature rise in direct burial, the current rating of the conductor tends to decrease as the moisture contents decrease. In other words, a conductor operating at the rated loading must have a higher temperature than the permissible limit given by the manufacturer. It can be concluded from Figure 3 that for the same temperature rise in a tube installation, the current rating of the conductor tends to decrease (from the rated loading given by the manufacturer) as the moisture content decreases (shown by the much lower rating in the fully dry environment). In other words, a conductor operating at the rated loading must have a higher temperature than the permissible limit. It is also clear that moisture migration does not have a significant effect on the conductor current rating in case of tube installation, due to the high temperature rise across the cable-tube air gap. However, overall moisture levels do have a significant effect, as can be seen for the fully dry environment (worst case) at different permissible temperatures.

The PU current ratings for direct burial and tube installation are compared for various installation environment conditions and are given in Figure 4. It is clear from Figure 4 that in cases (a), (b), and (c), the direct burial has higher current ratings; however, in case (d), the tube installation has higher current ratings. Therefore, it is suggested that tube installation should be preferred in the case of a fully dry environment, as in such a case the tube not only aids installation and the mechanical protection of the cable, it also slightly improves its rating.

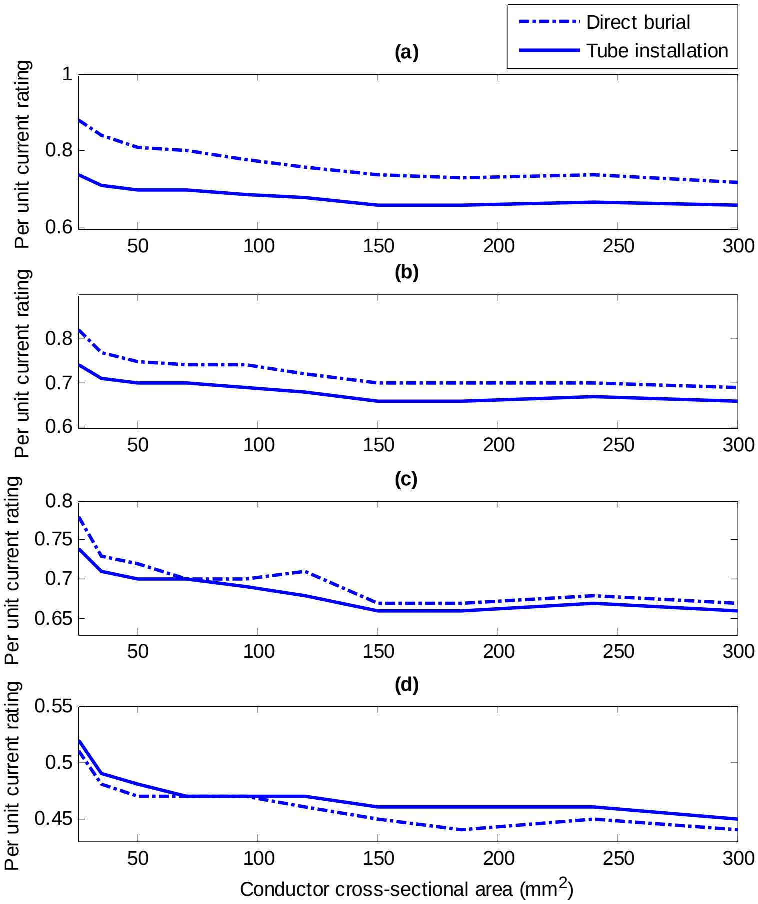

Fig. 4. Direct burial vs. tube installation for conductor at 70°C temperature in (a) no moisture, (b) moisture migration in controlled environment, (c) moisture migration in uncontrolled environment, (d) fully dry environment

The PU current ratings for direct burial and tube installation are compared for various installation environmental conditions at minimum and maximum conductor cross-sections. This analysis will be helpful to investigate the effect of conductor diameter on the calculation methodology. In the data sheet, the conductor has minimum and maximum cross-sectional areas of 16 and 300 mm^2, respectively. A comparative study for direct burial and tube installation has been carried out for minimum and maximum cross section areas as shown in Figures 5 and 6, respectively.

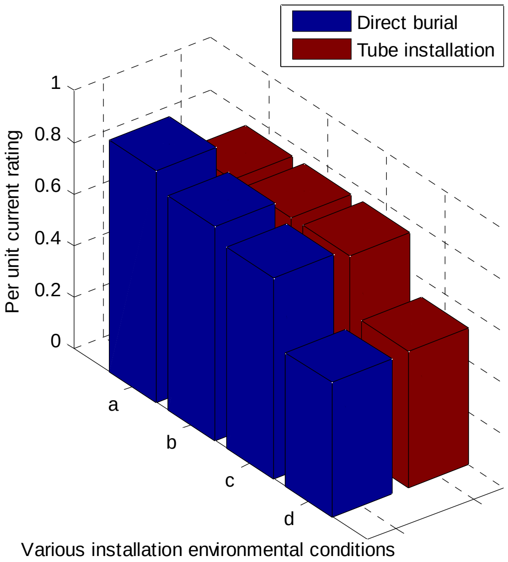

Fig 5. Direct burial vs. tube installation for conductor at 70°C temperature having the minimum cross- sectional area of 16 mm^2 under the two installation environmental conditions

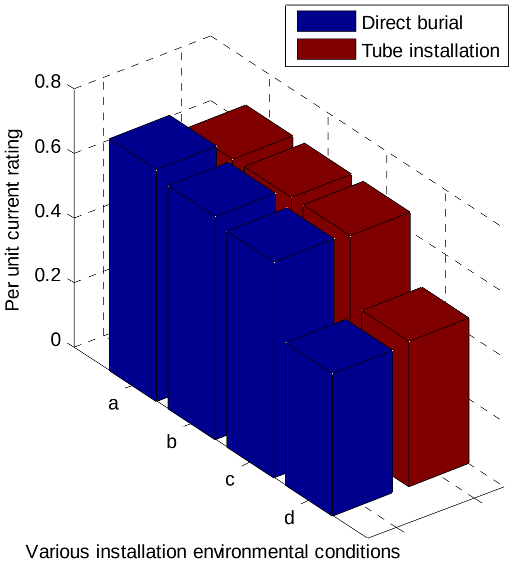

Fig 6. Direct burial v/s tube installation for conductor at 70°C temperature having maximum cross- sectional area of 300 mm^2 under various installation environmental conditions

It is revealed from Figure 5 that under the permissible limits of temperature rise, the conductor current rating is higher in the case of direct burial installation for the first three environmental conditions (a, b, and c). However, the conductor current rating is higher in the case of tube installation for the fully dry environmental case (case d). It can be concluded that the current rating pattern does not change under the different environmental conditions for minimum or maximum conductor cross-sectional area (see

Figures 5 and 6), which proves the applicability of this technique to determine current ratings for any size of conductor.

Some important observations

A comment should be made on multi-cable installations, as these are often encountered in real installations. Because the installation possibilities are almost infinite, a crude formula is given to compute the worst derating factor for *n* cables carrying similar loads. This is a lower limit (i.e. the error is on the conservative side).

$$\frac{I_{multi}}{I_{nom}} = \frac{1}{\sqrt{n}} \tag{1}$$

where I_{multi} / I_{nom} is the ratio (or derating factor) between the allowable steady-state rating for *n* cables and the nominal steady-state rating for a single (3-phase) cable installation.

The dimensions of LV cables are naturally smaller than MV and HV cables. This means that the air gap between a cable and its installation tube is greater in terms of the cable diameter. This tends to mean that the air gap around an LV cable equates to a larger equivalent thermal resistance, which in turn relates to a higher temperature difference between the cable and its tube than for larger cables. That is why moisture migration would appear to be less of an issue for LV tube installations.

The effect of moisture migration is very sudden and significant, however, in directly buried LV installations. The smaller thickness of insulation means the thermal gradients are higher close to the cable surface. The same thickness of dried out environment equates to a higher thermal resistance around heat sources of smaller diameter – so this also gives some clue as to the razor-edge nature of LV rating, when ampacity rather than voltage drop is the critical design parameter.

The fact that AXMK cables have no metallic sheath means that the assumptions of thermal symmetry in the cable and installation tube are less valid than in MV and HV cables. Assumptions of balanced loading across the 3 phases is also more questionable in LV installations, but it is felt that these issues are offset by the fact that we have based this report on steady-state evaluations. The fact that the load factor in LV installations is generally quite low gives a good safety margin, although it must be admitted that less is known about the actual currents at the low voltage level than at higher voltage levels.

In general, rating low voltage cables is problematic, because of the likelihood of other services in the thermal environment that may themselves be heat sources (other power cables, district heating pipes, etc) or will at least affect the heat dissipation in some way. The installation conditions at 0.7 m are extremely variable, it is likely that little attention is made to suitable backfill material around many LV installations and ambient temperature variations are likely to be quite significant. In general, while we can say that the temperatures of HV installations are likely to be close to our theoretical predictions, more error is likely to occur in MV cable rating, and a high degree of error is likely to occur in LV rating. This in some ways justifies the computation methods employed in these reports.

7. Conclusions

- An analytical formulation for the calculation of current loading for 3-phase LV power cables under various environmental conditions has been presented. The results are to a large extent confirmed by comparison with those obtained from FEMLAB.

- The moisture content decreases due to the moisture migration phenomenon occurring in the vicinity of a cable, the current rating of the conductor also decreases for the same permissible thermal limits. Therefore, it is suggested to load the cables at lower current ratings than those given in the specifications for safe and reliable operation.

- In case of direct burial or tube installation, the current rating decreases (from the rated loading given by the manufacturer) due to moisture migration. However, the effect is more significant in the case of direct burial.

- Slightly higher current ratings are obtained in the case of tube installation for a typical fully dry environment, but these ratings are substantially lower than the catalogue values!.

- The pattern of decreasing current rating due to moisture migration under various environmental conditions is the same for minimum or maximum conductor cross-sectional area, which proves the applicability of this technique for any size of conductor.

- In the worst case, fully dried out peaty native soil, the load capacity of the cables is reduced to less than 50% of the normal rating. This scenario is possible during a long-term dry period, especially if there is vegetation close to the cable route.

- This study will be useful for electric power utilities to revise allowable current ratings to avoid damage to their power cables, as well as for the safe and reliable distribution of power to their customers.

- Note that the report offers guidelines only, and that critical individual LV cable installations should be treated more thoroughly.

- There is no implied criticism of the catalogue ratings in this report – they are perfectly valid under the conditions they specify!

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Transformers Loading Conditions for Future Thermally Unfavourable Environments

Report for ILMUU2-Project

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CONTENTS

1 Introduction

Power transformers are used in power generation units, transmission and distribution networks to step up or down the voltage of the power system. The capacity is usually between a few MVA and about 100 MVA. To be able to use the real capacity of power transformers it is important to know the duration and level to which power transformers can be thermally stressed. Because of increasing age coupled with higher loading and the need to more efficiently utilise expensive components such as transformers, increasing demands are being imposed on the liquid and solid insulating materials with regard to operating reliability and overloading capability.

The impact of large power transformer failure on power systems is due to their high cost, the impact on system operation due to their location and role in the network, and the fact that they are encased in tanks of flammable and toxic fluid which is a potential risk to people, property and the environment [1]. These factors surely present a strong motivation for utilities to monitor the health of their power transformers.

Power transformers are likely to be the most expensive asset within electrical networks [2], and so their availability and reliability is of paramount importance. Their nominal life expectancy is expressed in years, corresponding to their nameplate rated load and ideal conditions [3]. Failure will eventually occur as the windings' paper insulation erodes past the limit where the structural and electrical stresses can be sustained. This unavoidable degradation is cumulative and is further increased by the presence of both heat and oil contaminants, including gases and water [4].

The designer aims to ensure that temperatures are kept to reasonable levels in a transformer when loaded up to continuous maximum rating. Practically, a power transformer has a significant thermal capacity largely arising from the insulating oil. This allows the possibility of loading for short periods beyond the continuous rated nameplate value [5]. Limitations on acceptable conductor and oil temperatures are typically stated in the transformer specification, and these in turn are likely to be based on recommendations in such documents as the international standard loading guide for oil immersed power transformers, IEC 354 [6].

A transformer's loading capacity is related to the exposure of its insulation to heat, the highest temperature of which is referred to as the hot spot temperature. The hot spot temperature effect on the winding paper insulation is used to quantify the limit of its temperature range over a calculated period of time. The problem, however, is that these limits are dynamic due to the changing transformer characteristics and varying ambient climate conditions.

In this work, steady-state calculations are performed using IEC guidelines to determine the hot spot temperatures of distribution and power transformers in the worst projected Finnish environment due to long summer periods. Moreover, the effect of increase in winding resistance due to increase in ambient temperatures has been taken into account. The primary goal is to investigate the possible extreme circumstances due to climate change. Transformers should be progressively de-rated under such circumstances for the safe operation of these components, which will not only prove cost-effective for utilities, but would also improve the reliability of the power supply to their valued customers.

2 The temperature effects in a transformer

When a current is passed through the conductor, heating losses are produced in the form of I^2R losses, where I is the magnitude of current passing through the conductor having resistance R. An equilibrium conductor temperature is reached if the heat can be removed at the same rate as that at which it is produced. Physical and chemical effects governing the interaction between materials are generally temperature dependent and chemical reaction rates typically increase with increasing temperature [5].

Monitoring a transformer through temperature sensors is one of the simplest and most effective monitoring techniques. Abnormal temperature readings almost always indicate some type of failure in a transformer. For this reason, it has become common practice to monitor the hot spot, main tank, and bottom tank temperatures on the shell of a transformer. As a transformer begins to heat up, the winding insulation begins to deteriorate and the dielectric constant of the mineral oil begins to degrade.

According to the IEC guide, the ageing of the paper insulation system is such that the stated transformer life can be achieved for a continuous maximum hotspot temperature of 98 °C. Beyond this temperature, it is assumed that the rate of ageing doubles for every increase of 6 °C. At temperatures of the order of 150 °C, accelerated ageing tests in the laboratory demonstrate that the useful life of the paper may only be a few days. This clearly limits the life of the transformer and is one of the governing factors on the maximum load that should be used [5].

3 Ratings calculations based on IEC354

Emergency and/or planned overloading of power transformers beyond their nameplate rating depends on several factors including design and operating characteristics, daily load curve, historical loading data, testing and maintenance program, and particular applications. The overloading capabilities depend primarily on the winding hottest spot temperature. Determining accurately the hottest-spot temperature is very critical to the transformer overall life expectancy assessment.

Short duration and cyclic loadings are normally calculated following the principles in IEC 354. The loading guide tables are based solely on the equations for winding hotspot and oil temperatures, without regard for other factors. This is because the effects such as heating by stray losses are very dependent on design and in any case not easy to calculate. However, in constructing loading guide tables, the transformer user needs to be aware of restrictions on loading other than winding temperature and the circumstances in which those restrictions might apply [5].

The IEC standard provides a series of simplified equations that describe a mathematical model for the calculation of operating temperatures in a transformer. The assumptions listed in these standards include: a linear temperature rise in the oil from the bottom of the tank to the top, a parallel temperature rise in the windings, and an allowance for stray losses that is used to assess the hot spot temperature. As this standard points out, for large power transformers, the results for hot spot temperatures (based on temperature rise tests) may not be valid due to the significance and complexity of the contribution of flux leakage to the heating of the windings. Therefore, this method has a limited use, restricted at or below the transformer's rated capacity. A further note in this standard adds that corrections to account for load losses and oil viscosity can be dismissed as either insignificant, or that the effects cancel each other.

4 Transformer loading guides

A number of semi-empirical equations have been derived to predict the hottest spot temperature rise in transformers at their rated full load. Of these, the most common model used for this and top oil temperature calculations is described in IEC 354 [6]. A simplified transformer temperature distribution based on this model is shown in Fig. 1. The steady state temperature relations in IEEE [4] are similar to Fig. 1, which have been extracted from the IEC loading guide. This diagram is based on the following assumptions, directly taken from [7]:

- The oil temperature inside and along the windings increases linearly from bottom to top.

- The winding temperature increases linearly from bottom to top, with constant temperature difference g.

- The hot spot temperature rise at the top of the winding is higher than the average temperature rise of the winding. To consider non-linearities such as the increase in stray losses at the top of the winding, the difference in temperature between the hot spot and the oil at the top of the winding is defined as Hg. The hot spot factor H may vary from 1.1-1.5, depending on the transformer size, short circuit impedance and winding design.

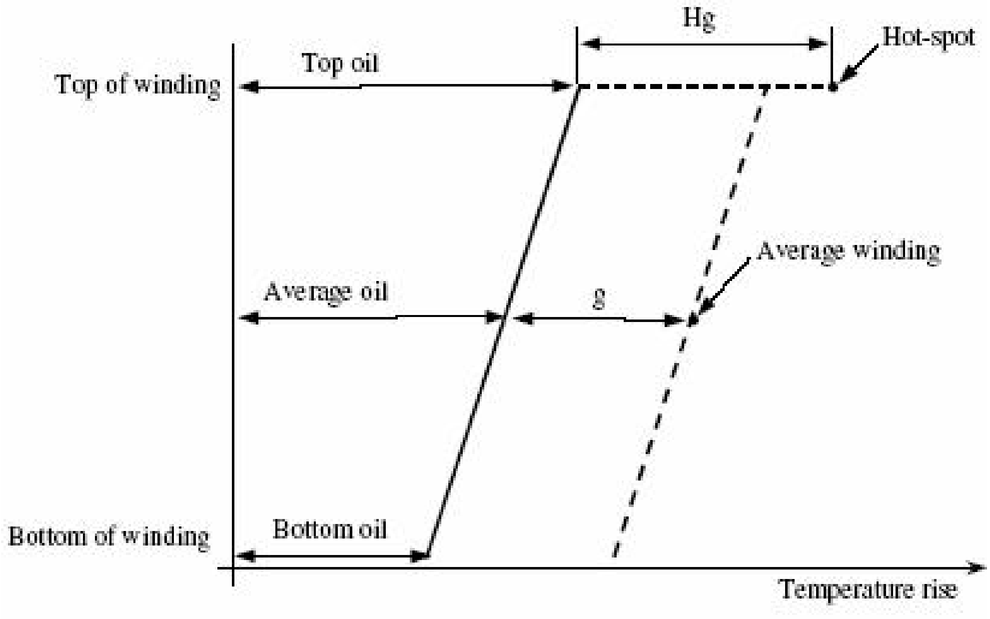

Fig. 1. Transformer thermal diagram according to IEC 354 [7]

4.1 Calculation of different temperatures in transformer

The ultimate hot spot temperature for a transformer under any load K is equal to the sum of the ambient temperature, the top oil temperature rise over ambient, and the hot spot temperature rise over top oil. This can be expressed by the equation below:

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \tag{1}$$

where

θ_A is the ambient temperature in °C
$\Delta\theta_{T0}$ is the top oil temperature rise over ambient in°C
$\Delta\theta_H$ is the hot spot temperature rise over top oil temperature in °C
θ_H is the ultimate hot spot temperature in °C

The top oil temperature over ambient temperature is given by the following equation:

$$\Delta\theta_{TO} = \Delta\theta_{TO-R}\left(\frac{1+R\cdot K^2}{1+R}\right)^n \tag{2}$$

where

$\Delta\theta_{TO-R}$ is the top oil temperature rise over ambient at rated load
R is the ratio of load losses at rated current to no load current losses

K is the load factor (supplied load/rated load)
n is an empirically derived exponent that depends on the cooling method

The hot spot temperature rise over top oil temperature is given by:

$$\Delta\theta_H = H \cdot g \cdot K^{2m} \tag{3}$$

where

$\Delta\theta_H$ is the hot spot to top oil rise
H is the hot spot factor due to increased eddy losses at the winding end
g is the average winding to average oil temperature rise at rated load
m is an empirically derived exponent that depends on the cooling method

The suggested exponents n and m define the non-linearity and depends on the transformer cooling method. The four modes of cooling used are: natural convection of oil in the transformer and natural convection of cooling air over the radiators (OA/ONAN), natural convection of oil with forced convection of air over the radiators (FA/ONAF), non-directed forced oil flow and forced air flow (NDFOA/OFAF), and directed forced oil flow and forced air flow (DFOA/ODAF). The exponents used are given in Table 1.

Table 1. Exponents used in temperature calculation equations [7]

Types of cooling	**IEC**		**IEEE**	
	n	***m***	***n***	***m***
OA/ONAN	0.9	0.8	0.8	0.8
FA/ONAF	0.9	0.8	0.9	0.8
NDFOA/OFAF	1.0	0.8	0.9	0.8
DFOA/ODAF	1.0	1.0	1.0	1.0

5 Simplified transformer overloading guide

It is quite common practice to exceed the nameplate rating when loading power and distribution transformers for short times. Simplified transformer overloading guidelines are take into consideration ambient temperature, nameplate rating, design fundamentals, long-time emergency loading, short-time overloading, moisture contents (every 0.5% increment of content reduces insulation life by half), etc. Some of the key features are depicted in Fig. 2 for clarity and better understanding [8]-[11].

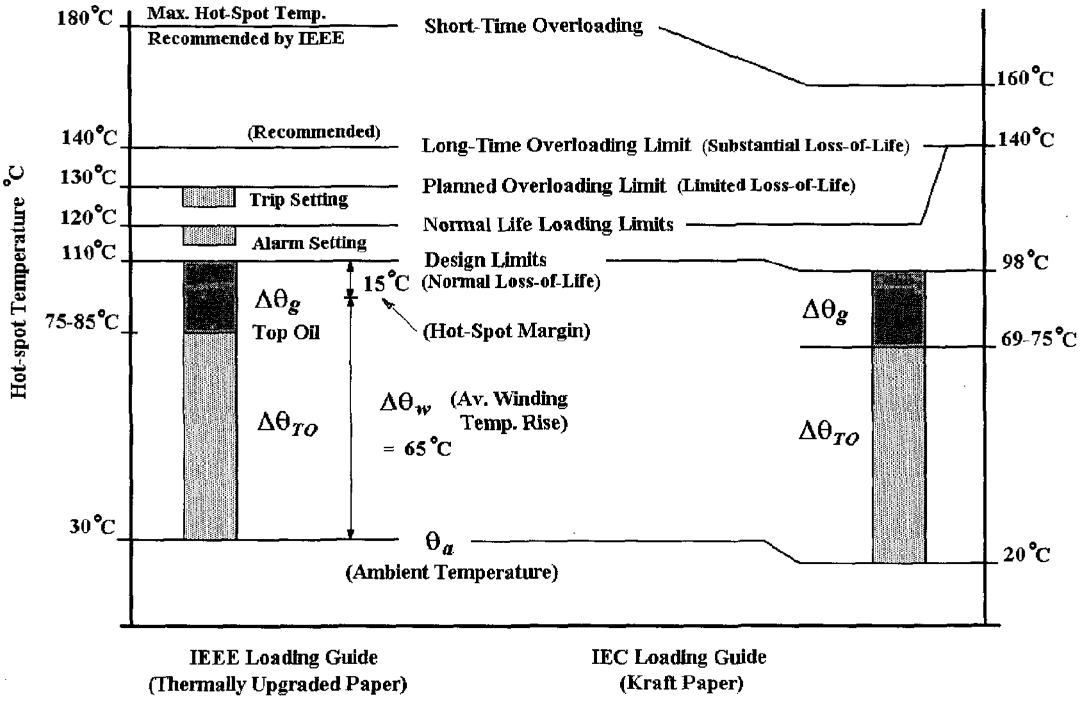

Fig. 2. IEEE and IEC temperature limits for various types of loading [11]

5.1 *Cyclic loading and winding temperature limits*

Transformer hot spot temperatures above 98 °C cause the winding insulation to age faster. The rate at which transformer insulation deteriorates increases exponentially with temperature up to 140 °C; it doubles for every temperature rise of 6 °C. The insulation will rapidly deteriorate at temperatures above this level.

Notwithstanding, transformers can occasionally be run over their nameplate rating for a limited period, i.e. a few days, without dramatically reducing the life of the transformer. The relative rate of using life is shown in Table 2 [12]. If, for example, a transformer is run at a continuous loading level that gives a winding temperature of 104°C, the ageing rate would be doubled, i.e. the transformer will age two days in one day. If such periods are restricted to a few days and do not occur very often, the loss of life over its normal life span will be negligible. The converse is also true, periods of lower than 98°C operation will tend to "pay back" periods of moderate overloading. The number of hours per day of operation at any given value of winding hot spot temperature that will use one day's life is shown in Table 3. A winding hot spot of 116°C that prevails for three hours would produce ageing equivalent to one day according to this modelling [12].

In general, the application of load in excess of nameplate rating involves a degree of risk and accelerated aging. These effects, taken directly from [13], can be summarized as follows:

- "For short term transformer failure, the main risk is the reduction of dielectric strength due to the release of gas bubbles in regions of high electrical stress. The probability of occurrence of these bubbles is closely related to winding insulation hot spot temperature and moisture content of insulating paper.

- Under overloading conditions, some components such as LTC contacts and bushing connections may develop high temperate leading to thermal runaway. High temperature may also occur in structures when the stray magnetic field increases beyond the saturation point of magnetic shields.

- For long duration overload, the main consequence is the thermal aging of solid insulation. With time, the cellulose chains undergo a depolymerisation process thus reducing the average length of cellulose chains and consequently reducing the mechanical strength of paper. This deterioration of paper is a function of time, temperature, moisture content and oxygen content. This effect is irreversible and forms the basis for transformer life duration."

Table 2. Relative rate of using life versus hot spot temperature [12]

Hot spot temperature (°C)	**Relative rate of using life**
80	0.125
86	0.25
92	0.5
98	1.0
104	2.0
110	4.0
116	8.0
122	16.0
128	32.0
134	64.0
140	128.0

Table 3. Number of hours per day versus hot spot temperature [12]

Hot spot temperature (°C)	**Hours per day**
98	24
101.5	16
104	12
107.5	8
110	6
113.5	4
116	3
119.5	2
122	1.5
125.5	1.0
128	0.75
131.5	0.5

6 Transformer overloading in the "worst" Finnish environment

The ambient temperature plays an important role for the determination of the hot spot temperature of a transformer determined by its loading profile. The hot spot temperature increases linearly by increasing the ambient temperature. Roughly, for every 1 °C increment in ambient temperature, the loading capacity can be decreased by 1% without any loss-of-life and vice versa.

On average, the ambient temperature is increasing to some extent every year due to the effect of overall global warming. This has been realized by monitoring the ambient temperatures over the last several years. The IEC loading guide is recommended for transformers operating with an ambient temperature of 20 °C. However, it does not give the actual hot spot temperature at varying ambient temperatures. Table 4 gives the future ambient temperatures of different locations in Finland [14]. It is revealed that ambient temperature may increase up to 33.8 °C in Helsinki during the years 2016–2045.

Table 4. Extreme temperatures (°C) for the periods 1961–1990 and 2016–2045 (Ilmatieteen laitos 1991) [14]

	Extreme temperatures (°C)			
	1961–1990		**2016–2045**	
Helsinki	-35.9	31.9	-28.4	33.8
Tampere	-37.0	31.6	-30.0	33.5
Vaasa	-38.6	31.8	-31.6	33.7
Kuopio	-39.3	32.6	-32.6	34.6
Kuusamo	-45.2	31.2	-39.2	33.1
Sodankylä	-44.7	31.3	-38.8	32.9

7 Calculations and results

In this project, steady-state calculations are performed to calculate the hot spot temperature of distribution and power transformers for possible future ambient temperatures in Finland varying from 20–40 °C. The value of g in the calculations is assumed to be 23 °C. The value of H is assumed to be 1.1 for distribution transformers and 1.3 for medium size and large power transformers. The value of $\Delta\theta_{TO-R}$ is selected in such a fashion (57.8 °C for distribution transformers and 54.1 °C for power transformers) that the ultimate hot spot temperature works out to be 98 °C for an ambient temperature of 20 °C.

7.1 Calculations for distribution transformers

The data for secondary line transformers is given in Table 5 [15]. The values of n and m are taken as 0.9 and 0.8, respectively, for the ONAN mode of cooling. R is defined as the ratio between load losses at rated current to no load losses. The load losses at rated current given by the manufacturer are estimated at an ambient temperature of 20 °C. However, their value increases due to increase in the resistance of the windings at higher ambient temperatures. A 0.4% increase in load losses due to a 1 °C rise in ambient temperature is a good approximation for this calculation. The load losses at rated current (given in Table 5) also include this incremental factor. For example, the load losses at rated current for a 50 kVA transformer are given as 1330 W at an ambient temperature of 20 °C [15]. The hot spot temperature is to be calculated at 33.8 °C (the projected maximum temperature in Helsinki in 2045). The increase in ambient temperature is 13.8 °C, which increases the load losses by 73 W. Therefore, the total load losses are estimated to be 1403 W. The value of R is re-calculated due to the increase in load losses. The rated load of the transformer slightly increases due to increases in load losses (temperature dependent) at higher ambient temperatures; therefore, the supplied load is also increased to the same extent for unity load factor conditions (K=1). For determining the actual de-rating factor of the transformers, the calculated value (including the effect of temperature dependent load losses) is divided by the same incremental factor.

The hot spot temperature for an ambient temperature of 33.8 °C (Helsinki maximum future temperature in 2045) is calculated to be 115 °C for a variety of distribution transformers. Conversely, the transformers should be de-rated to approximately 86–87% of their maximum load for a hot spot temperature of 98 °C (as per IEC guide). The value of the hot spot temperature is approximately the same for different ratings of transformers. The ratings of the transformers do not have significant effect on the load factor, i.e. the de-rated values of load factors for distribution transformers are in the same range.

The variations of hot spot temperature and load factor due to ambient temperature are calculated and given in Table 6 (for 500 kVA transformers having load losses of 5000 W at ambient temperature 20°C).

Table 5. Hot spot temperature calculations at extreme temperature (33.8 °C) for distribution transformers

Rating (kVA)	**Voltage level (kV/kV)**	**Mode of cooling**	**No load losses (W)**	**Load losses at rated current (W)**	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H **(for** K**=1)**	K **(for** θ_H**=98 °C)**
50	20/0.4	ONAN	150	1403	9.3	60.4	21.3	115.5	0.868
100	20/0.4	ONAN	245	1973	8.0	60.3	21.3	115.5	0.867
200	20/0.4	ONAN	465	2743	5.9	60.2	21.3	115.4	0.864
315	20/0.4	ONAN	680	3672	5.4	60.2	21.3	115.4	0.862
500	20/0.4	ONAN	930	5276	5.7	60.2	21.3	115.4	0.863
800	20/0.4	ONAN	1400	6859	4.9	60.2	21.3	115.3	0.861
1000	20/0.4	ONAN	1500	8864	5.9	60.2	21.3	115.4	0.864

Table 6. Hot spot temperature and load factor
calculations for various ambient temperatures (distribution transformer)

θ_A	θ_H (for K=1)	K (for θ_H=98°C)
20	98.0	1
21	99.3	0.990
22	100.5	0.981
23	101.8	0.971
24	103.1	0.961
25	104.3	0.951
26	105.6	0.940
27	106.8	0.931
28	108.1	0.921
29	109.3	0.912
30	110.6	0.901
31	111.9	0.891
32	113.1	0.881
33	114.4	0.872
34	115.6	0.861
35	116.9	0.851
36	118.2	0.841
37	119.4	0.831
38	120.7	0.821
39	121.9	0.811
40	123.2	0.800

7.2 Calculations for power transformers

The data for primary line transformers is given in Table 7 [15]. The assumptions stated in section 7.1 have also been implemented in the calculations for power transformers. The load losses at rated current (given in Table 7) also include the incremental factor explained in section 7.1. For example, the load losses at rated current for a 16 MVA transformer are given as 88 kW at an ambient temperature of 20 °C [13]. The hot spot temperature is to be calculated at 33.8 °C (Helsinki maximum future temperature in 2045). The increase in ambient temperature is 13.8 °C which increases the load losses by 4.9 kW, and so the total load losses are estimated to 92.9 kW.

The hot spot temperature for an ambient temperature of 33.8 °C (Helsinki's maximum future temperature in 2045) is calculated to be 115 °C. Conversely, the transformers should be de-rated to approximately 86-87% of their maximum load to maintain a hot spot temperature of 98 °C (as per IEC guide). The value of the hot spot temperature is approximately the same for different ratings of transformers. The ratings of the transformers do not have a significant effect on the load factor, i.e. the de-rated values of load factors for power transformers are in the same range. The variations of hot spot temperature and load factor due to ambient temperature are calculated and given in Table 8 (for a 20 MVA transformer having load losses of 106 kW at ambient temperature 20°C).

Table 7. Hot spot temperature calculations at extreme temperature (33.8 °C) for power transformers

Core	**Rating (MVA)**	**Mode of cooling**	**No load losses (kW)**	**Load losses at rated current (kW)**	R	$\Delta\theta_{T0}$	$\Delta\theta_H$	θ_H	K **(for** θ_H**=98 °C)**
Al	16	ONAN	16.1	92.9	5.8	56.4	25.2	115.4	0.865
Cu	20	ONAN	16.8	111.8	6.6	56.4	25.2	115.5	0.867
Al	25	ONAN	21.8	127.7	5.8	56.4	25.2	115.4	0.865
Cu	31.5	ONAN/ONAF	24.5	143.5	5.8	56.4	25.2	115.4	0.865
Al	40	ONAN/ONAF	33.5	187.8	5.6	56.4	25.2	115.4	0.865

Table 8. Hot spot temperature and load factor calculations for various ambient temperatures (power transformer)

θ_A	θ_H **(for** K**=1)**	K **(for** θ_H**=98°C)**
20	98.0	1
21	99.3	0.991
22	100.5	0.980
23	101.8	0.972
24	103.1	0.962
25	104.3	0.952
26	105.6	0.942
27	106.9	0.933
28	108.1	0.923
29	109.4	0.914
30	110.7	0.904
31	111.9	0.894
32	113.2	0.884
33	114.4	0.874
34	115.7	0.865
35	117.0	0.854
36	118.2	0.845
37	119.5	0.835
38	120.8	0.824
39	122.0	0.815
40	123.3	0.805

7.3 Calculation results

The plots are drawn from the calculations performed in the last two sub-sections. It is revealed from Fig. 3 that by increasing the ambient temperature, the hot spot temperature also increases. This relationship is not quite linear because the temperature dependent winding resistance effects have been taken into account. The load losses at rated load depend on the ambient temperature and this has been considered during the calculations. The effect of ambient temperature on the rating of transformers (load factor) is depicted in Fig. 4, which highlights the fact that transformers must be de-rated to avoid excessive ageing and loss-of-life.

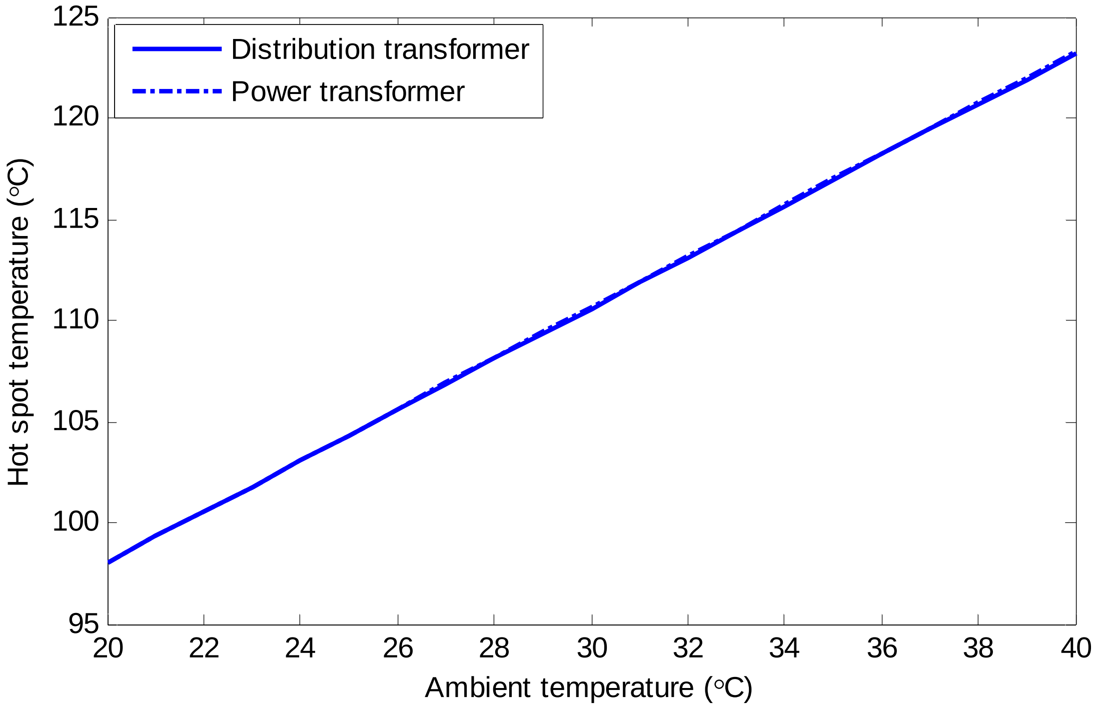

Fig. 3. Effect of ambient temperature on hot spot temperature for distribution and power transformers

It is expected that power transformers should be de-rated to a lower extent than distribution transformers (if we have a look in Fig. 3, where hot spot temperatures of power transformers seem slightly higher than distribution transformers). However, this fact is not revealed in Fig. 4 due to the different values of R for distribution and power transformers used in the calculations; the available data does not cover a variety of ratings. Moreover, the same values of m and n have been used for distribution and power transformers, but these values should be different for real analysis. For example, considering the NDFOA/OFAF mode of cooling for power transformers (n=1 and m=1) at the same ambient temperature, the hot spot temperature would go higher than a distribution transformer, while it would be de-rated to a lower extent than a distribution transformer. The difference in hot spot temperatures and rated loads of distribution and power transformers at extreme temperature (40 °C) in Fig. 3 and Fig. 4 are only 0.08% and 0.6%, respectively, which may increase by changing the mode of cooling for power transformers.

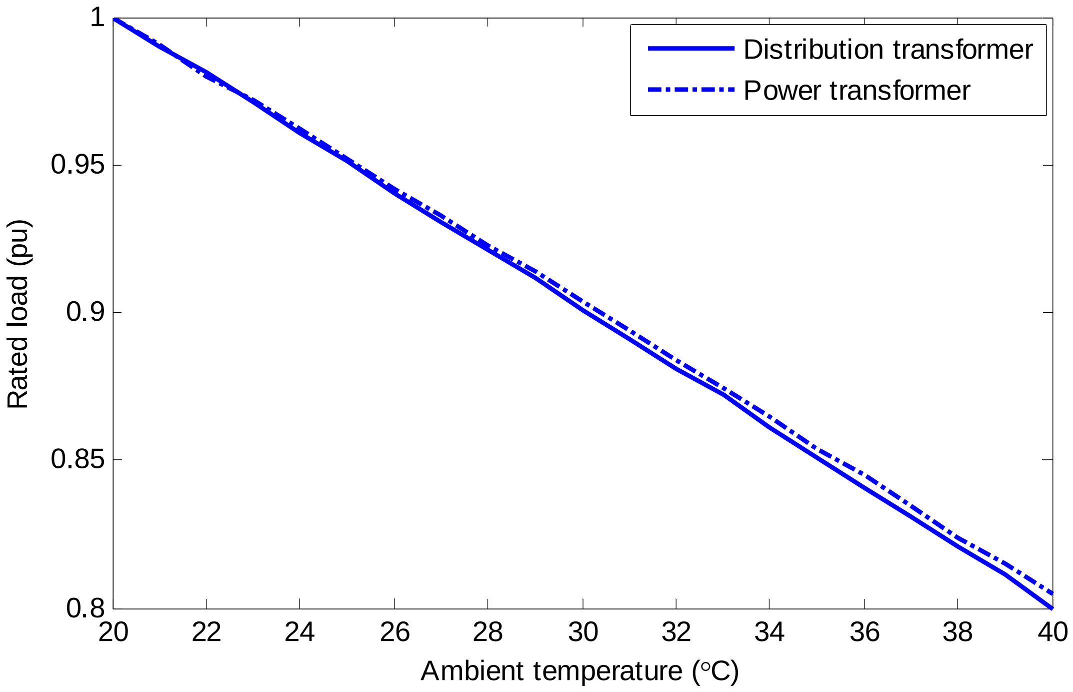

Fig. 4. Effect of ambient temperature on load factor for distribution and power transformers

8. Conclusions

- Hot spot temperature calculations for the future ambient temperature are performed using the IEC guide. The hot spot temperature increases almost linearly by increasing the ambient temperature. Conversely, the transformers should be de-rated from their given loading values (provided by the manufacturers).

- The hot spot temperature of distribution and power transformers may increase up to 115 °C in Helsinki (due to increase in ambient temperature up to 33.8 °C), therefore, the transformers must be progressively de-rated to 86–87% of their actual ratings without loss-of-life.

- If hot spot temperatures increase up to 115 °C, the relative rate of using life of transformers may decrease up to 8 times if operated continuously.

- To prevent transformers from early ageing, they should only be operated less than 3 hours per day in this worst environmental condition stated above.

- This study will be useful for electric power utilities to revise the allowable loadings of their transformers to avoid damage, as well as for the safe and reliable distribution of power to their customers.

The readers may observe that in the past, day time summer temperatures have been greater than 20 °C (see Table 4). Going into the future, the increase in ambient temperatures will tend to coincide with higher loading on existing power system infrastructure, meaning that temperatures will become more significant.

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Title

Recognizing climate change in electricity network design and construction

Abstract

The report presents how climate will change according to climate models concerning the planning and building of electric power networks from the present state to the period from 2016 to 2045. The essential impacts of changes in weather conditions on planning and building of electric network are defined regionally based on the climate change scenarios. The importance of the effects is shown as costs and failure durations for different line structures. Moreover, the influence of the climate change on the loading capacity of the power system components is presented. On the basis of all these factors it will be judged how strong an effect the climate change has in the present electric power network and how one should be prepared for it.

The stresses of the network will increase with climate change. This will increase the number of faults in current network and at the same time the total duration of faults, if improvements for reliability will not be increased. The effect is most significant for a bare overhead line network passing through a forest in rural areas. However, it is profitable to consider the final impacts in detail, because the weather causes faults in different ways depending on environmental conditions. Principally, the impact of climate change is remarkable especially in the regions that are even nowadays sensitive to weather. Poor access to the fault locations increases the repairing time. A forest sensitive to weather conditions increases number of faults and thus the total interruption time.

Based on the calculations the influence of climate change is much lower at the roadside and even lower in the fields. Urban networks are already mostly underground cable networks having considerably lower climate effects. Increasing costs due to the climate change increases also the profitability of the investments planned for improving the reliability of the network. The profitability and sufficiency of the investment aiming at reliable distribution always need a case-specific consideration. In regions sensitive to the crown snow loads it is useful to concentrate on trimming and clearing as well as to ensure the withstand strength of line and pole structures against snow loads.

The predictions always include some uncertainty. In this work the uncertainty is assessed by the different climate change scenarios as well as by estimating how significant the calculated results are compared to the total costs. The report estimates the risk caused by the climate change.

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Nimeke

Ilmastonmuutoksen huomioiminen sähköverkon suunnittelussa ja rakentamisessa

Tiivistelmä

Työssä esitetään, miten ilmasto ilmastomallien mukaan muuttuu sähköverkkojen suunnittelun ja rakentamisen kannalta nykytilasta ajanjaksoon 2016–2045. Ilmastonmuutosennusteiden perusteella määritetään sähköverkon suunnittelun ja rakentamisen kannalta olennaisten sääilmiöiden muutosten vaikutukset alueellisesti. Vaikutusten merkitys esitetään kustannuksina ja vika-aikoina eri johtorakenteille. Lisäksi esitetään ilmastonmuutoksen vaikutuksia sähköverkon komponenttien kuormitettavuuteen. Laskelmien perusteella määritetään, miten suuri ilmastonmuutoksen vaikutus on nykyverkossa ja miten siihen tulee varautua.

Ilmastonmuutoksen myötä verkon rasitukset kasvavat. Tämä lisää nykyverkossa vikojen lukumäärää ja samalla yhteenlaskettua vika-aikaa ellei luotettavuutta lisääviä panostuksia lisätä. Vaikutus on merkittävin maaseudulla metsässä kulkevilla avojohtoverkoilla. Lopullisia vaikutuksia kannattaa kuitenkin tarkastella yksityiskohtaisesti, koska sää aiheuttaa eri tavalla vikoja riippuen ympäristöolosuhteista. Pääasiallisesti ilmastonmuutoksen vaikutus on huomattava erityisesti nykyisin säälle herkillä alueilla. Huonot kulkuyhteydet lisäävät korjausaikaa. Säälle herkkä puusto lisää vikamääriä ja vastaavasti keskeytysten kokonaisaikaa. Ilmastonmuutos lisää luotettavuutta lisäävien investointien kannattavuutta. Näiden investointien kannattavuus ja riittävyys jakelun luotettavuuteen pyrittäessä on aina tarkasteltava tapauskohtaisesti. Tykkylumelle herkillä alueilla kannattaa panostaa raivaukseen ja oksimiseen sekä varmistaa johdon ja pylväsrakenteiden riittävä lujuus tykkykuormia vastaan.

Ennusteissa on aina epävarmuutta. Tässä työssä epävarmuutta arvioidaan vertaamalla neljän eri ilmastomallin ja päästöskenaarion yhdistelmän avulla laskettuja muutoksia. Lisäksi arvioidaan, miten merkittäviä laskelmien tulokset ovat verrattuna kokonaiskustannuksiin. Työssä arvioidaan ilmastonmuutoksen aiheuttamaa riskiä.

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