Loss of offsite power frequency estimates due to external events at a Finnish nuclear power plant

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Abstract: Loss of offsite power (LOOP) can occur due to reasons not originating from the nuclear power plant itself, commonly referred as external events. This study assessed frequencies of LOOP events due to external causes. Both technical failures (1-phase fault, permanent failure, major national grid failure) as well as extreme weather (lightning, strong wind, tornados, downbursts, freezing rain, wildfires, extreme temperature and heavy rainfall) have been accounted for and different mean times to repair (MTTR) have been assessed based on previous experiences on grid failures. The frequency of technical and lightning related failures for 400 kV power lines was assessed to be 2.88E-02/a and for 110 kV power lines substantially higher, 1.71E-01/a. The weather related 400 kV power line failure frequency was assessed to be 9.03E-03/a. Considering both 400 kV and 110 kV power lines, the frequency for a weather related power line failure was assessed to be 1.81E-02/a.

Keywords: PRA, Loss of offsite power, LOOP, External events, Grid failure

1. INTRODUCTION

It is recognized that the availability of AC power to commercial nuclear power plants (NPPs) is essential for safe operations and accident recovery. A loss of offsite power (LOOP) event, therefore, is considered an important contributor to total risk at nuclear power plants.

LOOP requires actuation of safety functions as the external grid is lost and electricity needs to be provided by other means to the nuclear power plant. Emergency diesel generators and back-up batteries are common means for providing an alternative source of AC power. A shutdown of the reactor is required as well to cut down on the need of heat transfer, which correlates strongly with the amount of electric power needed.

LOOP can occur due to external or internal reasons. External events are events that do not originate from the nuclear power plant itself, e.g. extreme weather and faults in the electrical grid. Internal events are events occurring within the nuclear power plant or switchyards. External and internal events causing LOOP can intersect in situation, where an external effect causes damages in an internal system, ultimately leading to LOOP. The scope of this report is limited to the assessment of external events.

The purpose of the report is to assess the probabilities of LOOP events to be used in the field of probabilistic risk assessment and other disciplines. The report consists of a methodology section describing the key principles used in the assessment of the probabilities, a Hanhikivi specific part presenting the main connections to the external grid, the frequency evaluations themselves and a summary to sum up the main results and key findings.

2. HANHIKIVI SITE CHARACTERISTICS

The nuclear reactor project site is situated on the Hanhikivi headland located roughly at 64°31’N 24°15’E.

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Fennovoima's nuclear power plant will be connected to the electric grid with 110 kV and 400 kV power lines at Hanhela and Valkeus substations. These Fennovoima's connecting lines will be located in Pyhäjoki and Raahe municipalities.

For a distance of seven kilometers, the 110 kV lines run in parallel with a 110 kV power line prepared by Puhuri Oy. In connection with the Hanhikivi 1 project, the national electricity transmission grid company Fingrid Oyj will strengthen its own grid in Pyhäjoki, Raahe, Merijärvi and Kalajoki municipalities.

The chosen route alternative (marked A1 in Figure 1 below) was drawn during the Environmental Impact Assessment (EIA) procedure based on feedback received on the different route options [1]. The selected route runs the first about four kilometers alongside the access road to the Hanhikivi 1 NPP. More detailed design of the power lines has begun and will continue until 2018.

Figure 1: The routes for Hanhikivi 1 NPP plant connecting powerlines. The original route alternative is marked with A and the chosen route alternative based on feedback from EIA procedure is A1.

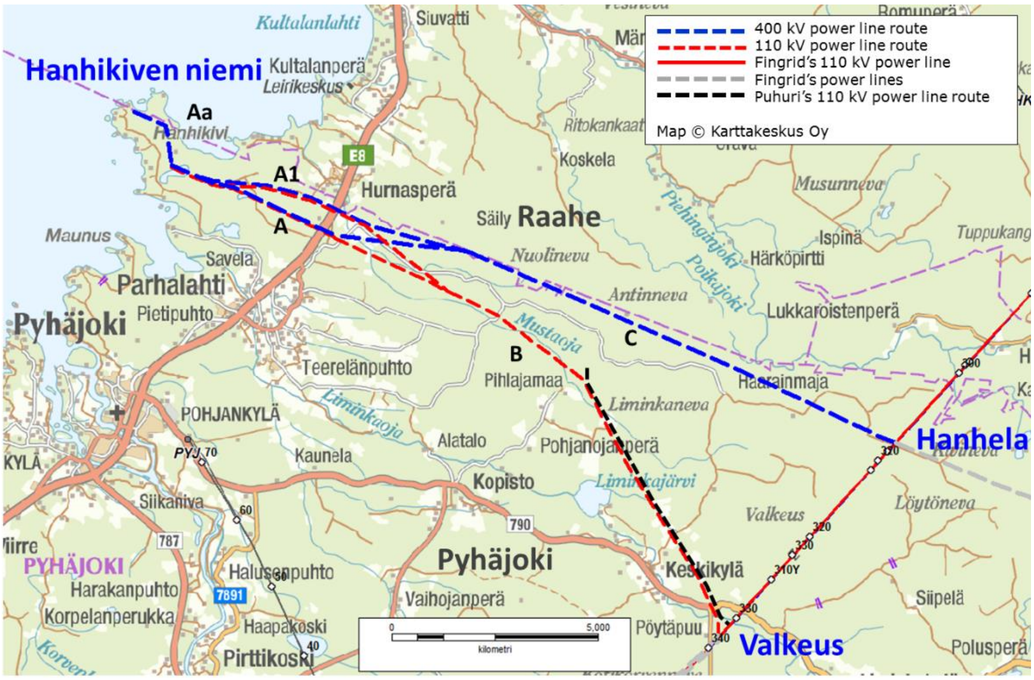


Table 1 presents the dimensions of the Hanhikivi plant site connecting power lines. In addition, the 110 kV power lines are dug underground at the Hanhikivi plant site area. This section of the power lines is not prone to extreme weather and also technical failures of an underground cable can be considered extremely unlikely. The underground section of the 110 kV power lines can thus be excluded from consideration. Analysis of LOOP frequencies will consider the sections separately. External threats are localized differently, taking into account the area of effect of the event examined. Some weather effects could affect only one of the lines.

Table 1: Hanhikivi plant site grid connection dimensions. [1]

Power line	Route	Length	Width of lane	Surface area
2 x 400 kV	Hanhikivi	1.45 km	76 m	0.11 km²
2 x 400 kV 2 x 110 kV	Hanhikivi – Hurmasperä	4.76 km	115 m	0.55 km²
2 x 400 kV	Hurmasperä – Hanhela	13.89 km	76 m	1.06 km²

2 x 110 kV	Hurmasperä - Pihlajamaa	6.24 km	46 m	0.29 km^2
3 x 110 kV[1]	Pihlajamaa – Valkeus	7.28 km	66 m	0.48 km^2

[1] only two of these are for the purposes of the Hanhikivi NPP

3. METHODOLOGY

The loss of offsite power frequencies due to external events are assessed through assessing frequencies to the following events:

- No electricity in one 110 kV power line
- No electricity in both 110 kV power lines
- No electricity in one 400 kV power line
- No electricity in both 400 kV power lines
- No electricity in both 400 kV and both 110 kV lines

The examination of these events has been chosen as the plant response differs within these events. Any single power line is alone capable of supplying electricity to necessary safety systems at the power plant, but the variety of events has been chosen to enable assessment of plant response in greater detail. Some operator/human actions or automation actuations may be needed in case one of the power lines becomes unavailable.

Both grid and weather related events leading to partial/complete failure of the power lines will be examined. The identified events compromising grid integrity that have been identified as possible in the vicinity of Hanhikivi are presented in Table 2.

Table 2: Grid and weather related failures examined for the Hanhikivi NPP.

Failure type	Failure cause
Technical	1-phase fault between Hanhikivi - Hanhela/Valkeus
	Permanent failure between Hanhikivi - Hanhela/Valkeus
	Major national grid failure
Extreme weather	Lightning
	Strong wind
	Tornados and downbursts
	Freezing rain
	Wildfires
	Extreme temperature
	Heavy rainfall

The probabilities of human or fauna cased failures have been estimated to be low and therefore have not been assessed.

1-phase technical failure is a short fault of the system in which the current is returned within 30 seconds. A permanent failure is an occurrence where repair times have been estimated to be approximately 10 hours.

The LOOP events are assessed according to the current knowledge of the grid connection planned for the Hanhikivi site (Figure 1). Some events can affect only one of the power lines whereas other events affect several or all of the power lines, depending on the localness of the phenomenon.

Additionally, the length of the LOOP events are assessed as mean times to repair (MTTR). The lengths of the MTTR have been assessed as engineering judgments relying on information on previous incidents. A MTTR of 15 hours is thus used for weather related events. Design basis exceeding natural phenomena are likely to cause vast damages to the grid and it is thus difficult to justify a shorter outage time. 15 hours is thus considered as a plausible best-estimate value. The value is also used in [2] for natural phenomena.

The duration of the outage in case of a major national grid failure is based on instructions made by the national electricity transmission grid operator Fingrid. It is stated that after a failure in the transmission grid the electricity should be restored within 30 minutes to an hour. 45 minutes can thus be considered as a best-estimate value. According to Fingrid's instructions, major power plants are preferred when restoring electricity. [2]

4. FREQUENCY EVALUATION

The occurrence probabilities are calculated separately for each event. The most actual data sets for Hanhikivi were utilized and they are presented separately in each subsection.

4.1. Technical failures

The relevant failure data of the Fingrid transmission network from the ENTSOE database covers 10 years in Finland, from 2006 to 2015 [3]. For some data, either shorter or longer observation periods have been available and they have then been utilized. The reliability database also includes information from all the other Nordic countries (Denmark, Iceland, Norway and Sweden) and the Baltic countries (Estonia, Latvia, and Lithuania). The statistics include 100 % of the Finnish 400 kV power lines, 100 % of the Finnish 220 kV power lines and 94 % of the Finnish 110 kV power lines.

The ten-year annual average of the number of grid disturbances is 417. On average, 80 disturbances per year caused energy not to be supplied in 2009-2015.

Following types of failures have been recorded in the failure database:

- Lightning
- Other environmental causes
- External influence
- Operation and maintenance
- Technical equipment
- Other
- Unknown

It shall be noted that the division to different failure types is not completely precise. The categories are not always accurately defined in the database, and the database acknowledges that unknown cause category is probably in large portion due to lightning and other environmental causes.

As can be seen from division of failures, the ENTSOE database covers the technical failures and the frequencies can thus be assessed directly based on the disturbance history retrieved from the database. Technical failures are divided into shorter 1-phase faults and permanent faults. The relevant failure data for Finland is presented in Table 3.

Table 3: Failure data for 110 kV and 400 kV Finnish national power lines, annual occurrences. Observation period 1996-2015. [3]

		Share of faults in different categories (%)								
	Faults per 100 km	Lightning	Other environmental	External influences	Operation and maintenance	Technical equipment	Other	Unknown	1-phase	Permanent
110 kV overhead	2.05	36	18	1	1	0	5	38	78	4
400 kV overhead	0.25	71	10	2	6	2	5	5	64	10

As the share of different categories is allocated only with an accuracy of 1 %, the failure share due to technical equipment can be anything from 0 to 0.5 % for 110 kV overhead power lines and from 1.5 to 2.5 % for 400 kV overhead lines. The average values of the range can be considered as the best-estimate values and are applied in calculations.

The frequency of short 1-phase faults due to technical failures is calculated with the equation

$$f_{1-phase} = L * N_{100km} * p_{technical} * p_{1-phase}, \quad (1)$$

where N_{100km} is the number of faults per 100 km of power line in the ENTSOE database, L is the length of the line section in question, $p_{technical}$ is the share of faults due to technical equipment, and $p_{1-phase}$ is the share of 1-phase faults compared to all faults.

Similarly, the frequency of permanent faults are calculated with the equation

$$f_{permanent} = L * N_{100km} * p_{technical} * p_{permanent}, \quad (2)$$

where $f_{permanent}$ is the frequency of permanent faults, N_{100}km is the number of faults per 100 km and $p_{permanent}$ is the share of permanent faults of all faults.

It is assumed that common cause failures can affect either both 110 kV power lines or both 400 kV power lines at the same time. In addition, an engineering judgment is applied, where 5 % of single power line technical failures are assumed to be common cause failures that affect both lines. The lengths of the power lines can be calculated from the information provided in Table 1. The results are presented in Table 4.

Table 4: Loss of offsite power frequencies and events due to technical failures.

Cause	Measure	Lines affected	Frequency (1/a)
Technical failure (1-phase)	Single failure	1. 400 kV	6.43E-04
	Single failure	2. 400 kV	6.43E-04
	Single failure	Either 400 kV	1.29E-03
	Common cause	2x 400 kV	3.22E-05
	Single failure	1. 110 kV	7.31E-04
	Single failure	2. 110 kV	7.31E-04
	Single failure	Either 110 kV	1.46E-03
	Common cause	2x 110 kV	3.65E-05
Technical failure (long)	Single failure	1. 400 kV	1.01E-04

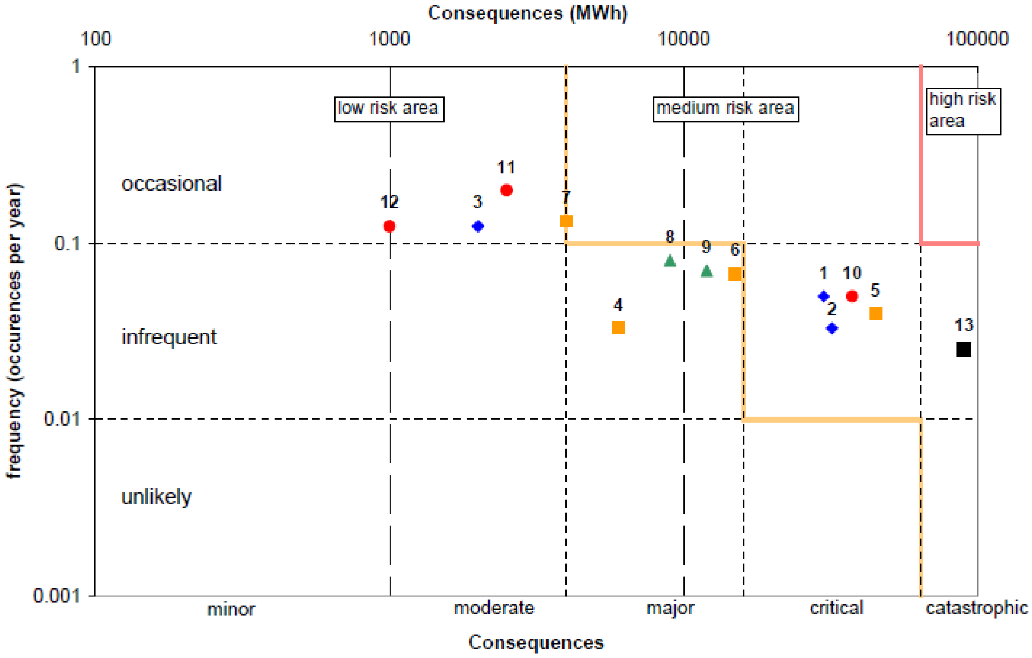
	Single failure	2. 400 kV	1.01E-04
	Single failure	Either 400 kV	2.01E-04
	Common cause	2x 400 kV	5.03E-06
	Single failure	1. 110 kV	3.75E-05
	Single failure	2. 110 kV	3.75E-05
	Single failure	Either 110 kV	7.49E-05
	Common cause	2x 110 kV	1.87E-06

4.2. Major national grid disturbance

The frequency estimate of a major national grid failure is based on the Master’s Thesis done for the Loviisa Nuclear Power Plant [2]. The same estimate is considered valid and applies to Hanhikivi 1 NPP risk modelling. The justification for the validity of the estimate is provided below.

The frequency estimate of 3.33E-2 /a (once in 30 years) presented in the Master’s Thesis [2] is based on an extensive report on the vulnerability of the Nordic power system [4]. The study is still the latest extensive research done on the topic in the Nordic countries. The study has considered two critical faults for the Finnish power system. Case one is an import case to Finland resulting in 10 000 MW power interruption with a maximum occurrence of once in every 20 years. Case two is a high export case from Finland resulting in an 8000 MW power interruption with a maximum occurrence of once in every 30 years. The frequencies are presented in Figure 2. The study included cases for all of the Nordic countries and the two other cases considered critical are rather well in line with the frequency estimates of critical errors in Finland (Case 5 in Figure 2, 6000 MW interruption in Southern Sweden and Case 10 in Figure 2, 15000 MW interruption in Southern Norway and Oslo).

Figure 2: Risk analysis for the present power system in the Nordic countries [4]. The number refers to the scenario. Scenarios 1 and 2 are the scenarios considered for the power system in Finland.



Especially the scenario 2 in the study [4] can be considered representative for a major national grid failure for Hanhikivi. The scenario is described as follows:

"This scenario assumes light load in Finland and high generation in the southern parts of Finland. In this situation there can be maximum power export to Sweden through AC connection in the north (1100 MW) and on the FennoSkan HVDC link in the South (550 MW). In this operating condition the transfer limits are determined from stability constraints. The critical contingency in this situation is outage of the FennoSkan link, which will increase power transfer on the interface P1 (three 400 kV lines from north to south in Finland) and on the Sweden-Finland interface. If a second line outage occurs, e.g. P1, this may cause undamped power oscillations that in the worst case could result in an almost total collapse of the Finnish power grid."

The probability estimate for scenario 2 in study [4] was a maximum of once in every 30 years and thus the frequency estimate of 3.33E-2 /a for a major national grid failure for Hanhikivi 1 NPP seems justified. There have also been two critical national grid failures in the Nordic countries (Sweden 1983 and Southern Sweden/Eastern Denmark 2003) during the time window of the study 1983-2003 [5]. With regard to two critical incidents in all four of the Nordic countries during the observation time of 21 years, the frequency estimate for a major grid failure is in the right range considering the data available.

However, it shall be noted that the Fenno-Skan 2 (800 MW), the second cable of the Finland-Sweden submarine power connection, became fully operational in December 2011. The submarine power connections Estlink 1 (350 MW) and Estlink 2 (650 MW) have also become fully operational in January 2007 (former) and March 2014 (latter) providing interconnection between the Baltic and Nordic electricity markets. It is possible that the connections have a stabilizing effect on the grid disturbances and the probability estimates of the study [4] and Master's Thesis [2] should be updated. In the absence of new extensive research considering the vulnerability of the Nordic power system, the existing value can be considered as a slightly conservative estimate for the major national grid disturbance at Hanhikivi NPP. It is out of the scope of this report to perform extensive research on the Nordic power system stability and currently most up-to-date research results have been utilized in the frequency assessment.

4.3. Extreme weather conditions

4.3.1 Lightning

Loss of offsite power event frequencies due to lightning are assessed based on the failure data from the ENTSOE database [3]. The method used is similar as presented for technical failures in Section 4.1. The relevant data is presented in the same section. In addition, half of the share of fault in the category "Unknown" is allocated to lightning in both 1-phase and permanent failures. This is due to the report [3] evaluating the unknown cause as follows: *"A large number of disturbances with unknown cause probably have their real cause in the categories other environmental cause and lightning."*

1-phase lightning caused faults are calculated with equation

$$f_{1-phase} = L * N_{100km} * p_{lightning} * p_{1-phase}, \quad (3)$$

where N_{100km} is the number of faults per 100 km of power line in the ENTSOE database, L is the length of the line section in question, $p_{lightning}$ is the share of faults due to lightning (and 50 % of the unknown cause), and $p_{1\text{-}phase}$ is the share of 1-phase faults compared to all faults.

Permanent lightning caused failures are calculated similarly with the equation

$$f_{permanent} = L * N_{100km} * p_{lightning} * p_{permanent}. \quad (4)$$

It is conservatively assumed that a lightning caused fault would affect both power lines in the same lane. A permanent common cause failure to all power lines between Hanhikivi and Hurmasperä, where the two 110 kV and two 400 kV power lines share the same lane, would need a very high peak current lightning, which is highly unlikely. It is thus assumed that a permanent CCF occurs with a 5 % probability from the 400 kV power line permanent failure frequency between Hanhikivi and

Hurmasperä. 1-phase faults are extremely unlikely to affect all 4 power lines simultaneously and a common cause for 1-phase faults has thus not been considered.

The results are presented in Table 5.

Table 5: Loss of offsite power frequencies and events due to lightning failures.

Cause	Lines affected	Frequency (1/a)
Lightning failure (1-phase)	2 x 400 kV	2.36E-02
	2 x 110 kV	1.61E-01
Lightning failure (long)	2 x 400 kV	3.69E-03
	2 x 110 kV	8.24E-03
	2 x 400 kV, 2 x 110 kV	4.37E-05

4.3.2 Strong wind

Strong wind has a large effect area. The design basis exceeding wind speeds are thus likely to damage all of the 400 kV and 110 kV power lines and cause a complete grid connection failure. The limit wind speed for a structural failure has been estimated to be 39 m/s at a height of 30 meters. It is assumed that a 3 second gust is enough to damage the transmission lines. Consequence of strong wind is the loss of both 110 kV and both 400 kV power lines.

Return periods for different wind speeds in Pyhäjoki have been assessed in [6]. For 3 second gust data from Raahe Lapaluoto weather station (1996-2013) has been used. The frequency of wind speed exceeding 39 m/s at 30 meters height was interpolated from the results in the report and assessed to be $2 \cdot 10^{-4}$ /a.

4.3.3 Tornados and downbursts

Tornados and strong wind gusts (i.e. downbursts) are phenomena related to thunderstorms. Tornados produce rotational horizontal high-speed winds while downbursts are straight line winds, both occurring at ground level.

Return periods for tornados and downbursts of different Fujita classes have been assessed in [7]. In the examination of LOOP events, it has been assumed that tornados and downbursts of the Fujita class F1 (estimated wind speed according to enchanced Fujita scale 38 - 49 m/s) damage the power lines. The annual probabilities of exceedance for tornados and downbursts per square kilometer are presented in Table 6. The destruction path lengths are also presented in the same table. It shall be noted that the report [7] derives the downburst destruction path lengths from the tornado destruction path lengths through simple assumptions, they are not based on extensive research or empirical data. The results are thus highly conservative. For comparison, [2] estimates the destruction path length of a F3 downburst to be 5 kilometers, whereas the report [7] suggests an area of influence of 7.63 km² and destruction path length (assuming the same width-length ratio as suggested) of 27.4 km.

Table 6: The annual probabilities of exceedance for tornados and downbursts per square kilometer along with the destruction path lengths. [7]

	Fujita scale	Probability (1/(km^2 a)	Destruction path length (km)
Tornado			
	F5	2.61E-08	54.6
	F4	1.26E-07	43.6
	F3	6.08E-07	22.5

	F2	2.94E-06	10.7
	F1	1.42E-05	4.7
Downburst			
	F3	9.02E-06	27.4
	F2	4.35E-05	21.9
	F1	2.10E-04	11.3

The power line sections have been divided into three parts in the examination:

- Hanhikivi, length 1.45 km (2 x 400 kV power lines on plant site)
- Hanhikivi – Hurmasperä, length 4.76 km (all power lines on the same route)
- Hurmasperä – Hanhela/Valkeus, length 13.89 km (according to the longer of the two alternative routes), average distance of power lines routes 2.5 km (Figure 1)

For each tornado and downburst it is conservatively assumed that the target area is defined by "destruction path length" multiplied by "power line section length". The target area is the area where the tornado or downburst should be formed in order to possibly cause power line damage. The tornado or the downburst can cross the power lines at any place on the power line route. By assuming the length of the power line section as the target area width the various possibilities are accounted for in a conservative manner. An additional factor of 0.5 is added to the probability calculation to account for the fact that the tornado or the downburst has to be moving towards the power line routes in order to cause damage.

In addition, on the Hurmasperä – Hanhela/Valkeus part of the route different conditional probabilities for the damage extents have been applied and are presented in Table 7. The probabilities account the fact that the average distance between the different routes is approximately 2.5 km and the tornado or downburst can thus damage only the power lines of one route. For example, for an F1 tornado the destruction path length is 4.7 km and the damage of both 400 kV and 110 kV power lines is thus assumed with a conditional probability of 1 – (2.5 km / 4.7 km) ≈ 0.5. Damage of either 110 kV lines or 400 kV lines only are assumed equally probable thereafter.

Table 7: Conditional probabilities of the damage extent for the Hurmasperä – Hanhela/Valkeus part of the power line route.

	Fujita scale	400 kV and 110 kV power lines are damaged	110 kV power lines are damaged	400 kV power lines are damaged
Tornado				
	F5	1	0	0
	F4	0.95	0.025	0.025
	F3	0.9	0.05	0.05
	F2	0.75	0.125	0.125
	F1	0.5	0.25	0.25
Downburst				
	F3	0.95	0.025	0.025
	F2	0.9	0.05	0.05
	F1	0.8	0.1	0.1

An additional factor of 0.1 is applied to the results of downbursts. This is due to the fact that the current method presented in [7] is mainly based on assumptions derived from tornado data only making it a very conservative approach. With this conservative approach all of the power lines would be lost with an annual probability of 2.92E-02 (once in 34 years in Hanhikivi). This is not realistic as the study considers only a combined effect area of 510.7 km² for the largest downburst class F3, for example. Extrapolating the result to whole Finland (338 424 km²) in proportion of the areas would mean 19 events of this extent happening in Finland annually. This would be of a nationwide interest and reported largely in the media. However, this is certainly not the case now and a factor of 0.1 can thus be applied to remove some of the excess conservatism. Also after applying this additional factor the results related to downbursts can still be considered conservative. When sufficient data exists or new methods are created for the evaluation of downburst probabilities, this part of the report should to be updated as well.

To summarize the calculation methods, the different scenario frequencies of different Fujita-scale tornados are calculated with the following equations:

$$f_{tornado\_x} = p_{tornado\_x} * L_{dl} * W_{pl} * p_w, \quad (5)$$

where $f_{tornado\_x}$ is the damage frequency of the examined Fujita-scale (F1-F5) tornado, $p_{tornado\_x}$ is the annual probability of the examined Fujita-scale tornado per square kilometer, L_{dl} is the destruction path length, W_{pl} is the power line section length and p_w is the probability that the tornado is moving towards the power lines. The power line section length between Hurmasperä and Hanhela/Valkeus is allocated to different events by multiplying the length of the power line with the factors presented in Table 7.

The downbursts are calculated similarly:

$$f_{downburst\_x} = 0.1 * p_{downburst\_x} * L_{dl} * W_{pl} * p_w \quad (6)$$

The results are presented in Table 8.

Table 8: Damage frequencies of the power lines due to tornados and downbursts.

	Fujita scale	400 kV and 110 kV power lines damaged (1/a)	110 kV power lines are damaged (1/a)	400 kV power lines are damaged (1/a)
Tornado				
	F5	1.33E-05		1.03E-06
	F4	4.93E-05	9.54E-07	4.94E-06
	F3	1.18E-04	4.75E-06	1.47E-05
	F2	2.39E-04	2.73E-05	5.01E-05
	F1	3.91E-04	1.16E-04	1.64E-04
	SUM	**8.10E-04**	**1.49E-04**	**2.35E-04**
Downburst				
	F3	2.22E-04	4.29E-06	2.22E-05
	F2	8.22E-04	3.31E-05	1.02E-04
	F1	1.88E-03	1.65E-04	3.37E-04
	SUM	**2.93E-03**	**2.02E-04**	**4.61E-04**

4.3.4 Freezing rain

Freezing rain develops as falling snow encounters a layer of warm air deep enough for the snow to completely melt and become rain. The rain then falls through a shallow layer of cold temperatures, below 0 °C, near the surface. When this rain becomes supercooled (temperature below 0 °C), it freezes on contact with e.g. power lines adding weight to the structures. Subcooled rain (temperature above 0 °C) can also freeze upon contact, if the contact surface is at below-zero temperature.

The frequency of LOOP due to freezing rain can be estimated by using the results from Finnish Meteorological Institute’s climate simulations and historical data sets [8]. Through years from 1979 to 2000, 14 days were observed to have significant freezing rain events in Finland. Based on the observed events and climate model simulations that used the observed events as input data, freezing rain hazard curves for different nuclear power plant sites in Finland were retrieved.

According to experiences from Canada, freezing rain events with the accumulated amount of 30 – 35 mm have been reported to cause collapsing or falling of power lines and pylons due to the weight of the gathered ice, leading to power outages of over a week. 40- 45 mm accumulated freezing rain events have been reported to cause long lasting and even wider spread power outages. [9]

Based on the experiences mentioned, a damage to large power lines (110 kV and 400 kV) has been assumed when the freezing rain accumulated amount reaches 40 mm. The corresponding frequency of a 40 mm freezing rain in Hanhikivi, retrieved from the hazard curve presented in [8] is $2.15 \cdot 10^{-7}$ /a for climate conditions in 2060-2099. The estimation for current conditions is even less. In addition, the frequency of LOOP due to snow load (hard rime) is estimated to be close to the freezing rain LOOP frequency. The combined LOOP frequency due to freezing rain or snow is thus assessed to be $4.31 \cdot 10^{-7}$ /a.

4.3.5 Wildfires

The frequency of LOOP due to wildfire can be estimated by using the forest fire data gathered by the Finnish Forest Research Institute. The data of forest fires covers the years 1980-2013 (apart from year 1993) [10]. The data consists of 33122 forest fires with a total burnt area of 16686 hectares. As an annual average 1004 forest fires have been observed with an average burnt area of 0.50 hectares per forest fire. As the data shows, large forest fires are highly unlikely in Finland as the fires are extinguished effectively before they start spreading uncontrollably.

The whole forest land and poorly productive forest land of Finland is 22 820 000 hectares altogether. Of this, 2 737 000 hectares are located in Northern Osthrobotnia, where the Hanhikivi 1 NPP is being built. [10] Assuming forest fires equally probable throughout Finland, there is thus a 12 % chance of a specific forest fire taking place in Northern Ostrobothnia.

The annual average of forest fire in Northern Ostrobothnia can thus be estimated:

$$1004\ \frac{forest\ fires}{year} * 0.12 = 120\ \frac{forest\ fires}{year}$$

For simplicity, the burnt area has been assumed to be of a round shape. A 0.5 hectare area has thus a diameter of 80.1 m. As no trees exist on the power line lane area itself, this has been applied as the examined lane width. The lane width accounts for the fact that the forest fire does not have to ignite precisely next to the power line lane area. The length of the diameter has been added only from one side of the power line lane as the probability of the wind blowing the fire towards the power lines (0.5) has to be accounted for as well. The effect areas with account to wildfires are presented in Table 9. The area within Hanhikivi plant site (2 x 400 kV power lines, 1.45 km length) has not been considered as the plant site has continuous monitoring, constant presence of personnel and its own fire department, which is likely to extinguish the fires within the plant area very quickly. The plant area also has relatively little trees.

Table 9: Effect areas of Hanhikivi plant site grid connections with regard to wildfires.

Power line	Route	Length	Width of lane	Surface area
2 x 400 kV 2 x 110 kV	Hanhikivi – Hurmasperä	4.76 km	80.1 m	0.38 km²
2 x 400 kV	Hurmasperä – Hanhela	13.89 km	80.1 m	1.11 km²
2 x 110 kV	Hurmasperä - Pihlajamaa	6.24 km	80.1 m	0.50 km²
3 x 110 kV	Pihlajamaa – Valkeus	7.28 km	80.1 m	0.58 km²

As the effect areas are fairly small, it is likely that the small fires do not generate enough heat to damage the grid components. The tall trees will also be cleared from a minimum 10 m distance from the power lines [1], which decreases the heat load to the grid components significantly. Thus, if there is a fire in the power line area, LOOP is assumed with a 10 % probability. The effect area is then divided with the total forest land in Northern Ostrobothnia to retrieve the probabilities of LOOP events. The loss off offsite power frequencies due to wildfire are presented in Table 10.

Table 10: Loss of offsite power frequencies due to wildfires.

Power lines lost	Frequency (1/a)
2 x 400 kV, 2 x 110 kV	1.67E-04
2 x 400 kV	4.88E-04
2 x 110 kV	4.76E-04

4.3.6 Extreme temperature

The temperature variation design value for Finland has been assessed to be from +40 °C to -50 °C [11]. Of these values, the temperature tolerance of low values is of main interest as electric equipment may fail when the temperature is below the design value. It is assumed that high temperatures do not cause a grid failure, or such high temperatures with sufficient duration do not occur at the Hanhikivi site with any risk-significant frequencies.

Another effect of extreme temperatures is the thermomechanical load caused by temperature alterations. With modern solutions this has been accounted for. An expansion bus support can be applied between two consecutive bus tubes. This allows the power lines to expand (or contract) without causing thermomechanical load to the power lines.

The temperature tolerance is compared to the Finnish Meteorological Institute's extreme temperature frequency assessment [12]. The extreme temperature distribution gives the annual frequency for air temperature induced LOOP. The probability of temperature under -50 °C was assessed to be negligible (probability $<<10^{-8}$ /a).

4.3.7 Heavy rainfall

The Hanhikivi headland area is a low-lying land uplifting coast, the typical features of which include seaside meadows and paludifing shallow bays. The most prevalent habitat type on the Hanhikivi headland is the forests of land uplift coast. The area is a significant natural forest succession site, but there are no mature forests in the area. The loose soil in the Hanhikivi headland is mainly moraine. The bedrock is mainly metaconglomerate. [13] Generally, the terrain is very even and low-lying.

Considering the makeup and geographical nature of the area, heavy rainfall is considered extremely unlikely to cause loss of offsite power events. Heavy rainfall is not capable of causing shifts in the low-lying terrain either due to the lack of steep hills.

5. SUMMARY AND CONCLUSIONS

The summary of the results assessed for loss off offsite power events caused by technical failures are presented in Table 11.

Table 11: Loss of offsite power frequencies and events due to technical reasons.

Cause	Measure	Lines Affected	Frequency (1/a)	MTTR
Technical failure (1-phase)	Single failure	1 x 400 kV	1.29E-03	30 seconds
	Common cause	2 x 400 kV	3.22E-05	30 seconds
	Single failure	1 x 110 kV	1.46E-03	30 seconds
	Common cause	2 x 110 kV	3.65E-05	30 seconds
Technical failure (long)	Single failure	1 x 400 kV	2.01E-04	10 hours
	Common cause	2 x 400 kV	5.03E-06	10 hours
	Single failure	1 x 110 kV	7.49E-05	10 hours
	Common cause	2 x 110 kV	1.87E-06	10 hours
Major national grid failure		2 x 400 kV, 2 x 110 kV	3.33E-02	45 minutes

The summary of results assessed for loss of offsite power events caused by weather related events are presented in Table 12.

Table 12: Loss of offsite power frequencies due to weather related events.

Cause	Measure	Lines Affected	Frequency (1/a)	MTTR
Lightning (1-phase)	Common cause	2 x 400 kV	2.36E-02	30 seconds
	Common cause	2 x 110 kV	1.61E-01	30 seconds
Lightning (long)	Common cause	2 x 400 kV	3.69E-03	15 hours
	Common cause	2 x 110 kV	8.24E-03	15 hours
	Common cause	2 x 400 kV, 2 x 110 kV	4.37E-05	15 hours
Strong wind	Over 39 m/s	2 x 400 kV, 2 x 110 kV	2.00E-04	15 hours
Tornado	Over 39 m/s	2 x 400 kV	2.35E-04	15 hours
		2 x 110 KV	1.49E-04	15 hours
		2 x 400 kV, 2 x 110 kV	8.10E-04	15 hours
Downburst	Over 39 m/s	2 x 400 kV	4.61E-04	15 hours
		2 x 110 kV	2.02E-04	15 hours
		2 x 400 kV, 2 x 110 kV	2.93E-03	15 hours
Freezing rain or snow		2 x 400 kV, 2 x 110 kV	4.31E-07	15 hours
Wildfire		2 x 400 kV	4.88E-04	15 hours
		2 x 110 kV	4.76E-04	15 hours
		2 x 400 kV, 2 x 110 kV	1.67E-04	15 hours

To summarize the key results, the assessed LOOP values (loss of both 110 kV and both 400 kV power lines) with regards to different mean times to repair are:

- MTTR 45 minutes: 3.33E-02 /a
- MTTR 15 hours: 4.15E-03 /a

The study can be further improved at later stages by removing excess conservatism, when new data or improved assessment methods are available. Especially the assessment considering downbursts of different Fujita classes is rather scarce and based on simple assumptions. It would be beneficial to reassess the downburst LOOP frequencies once more appropriate methodologies have been developed. The frequency of a major national grid disturbance could also be re-evaluated when Nordic power system vulnerability studies, which take into account the new grid connections to other countries and other changes in the grid, have been performed.

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