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Writer: **Heidur Thorisdottir**	Heiður Þorisdóttir ………………………………………… (Writer's signature)

Faculty supervisor: Ove Njå

External supervisor(s): Dóra Hjálmarsdóttir

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- identification of critical factors

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Last but not least, I would like to thank my family and friends for their love and support and for lifting my spirit when the workload got overwhelming.

ABSTRACT

In Iceland, as in many other countries, the functioning of society is highly dependent on so-called critical infrastructures. These include the electrical system, composed of installations that produce, transmit and distribute electricity to users. To protect the system from harm and secure its continuous operation, the electrical operators must be ready to manage demanding situations and respond to unwanted events. One of the phenomena that can cause a disruptive situation is the ice-covered volcano Öræfajökull. Recent seismic unrest in the area indicates that the volcano is preparing for an eruption. Such an eruption would typically be accompanied by a *jökulhlaup* (glacial outburst flood) and widespread tephra fallout, both of which could have severe impact on the electrical system and the Icelandic society in general.

The goal of this thesis is to identify critical factors: principles, organizational factors and external influences, that electrical operators should account for in their emergency management for a "large-scale" in Öræfajökull. With the help of 6 sub-questions, the operators´ current form of emergency management and its importance to society was assessed. Important characteristics were detected by comparing this to widely accepted theoretical models. 12 critical factors for the emergency management of the operators were identified. They were sorted into planning factors, organizational factors, factors related to uncertainties surrounding the event and system specific factors. Most of these factors are general and can apply to the emergency management for any catastrophic event affecting the electric system. The factors do not provide detailed guidelines on how electrical operators should handle their emergency management but are viewed as important values, recommendations or principles for the operators to have in mind.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUTION

1.1. Background

In Iceland, as in most of the industrialized world, the functioning of society is dependent on the so-called critical infrastructure. In the Norwegian Public Report 6:2006 critical infrastructure is defined as “the constructions and systems that are strictly necessary to maintain critical social functions”, that again covers “the society’s basic needs and feeling of security” (Ullring et al., 2006).

In Iceland, critical infrastructure is sorted into 8 categories (Icelandic Ministry of the Interior, 2015):

- Telecommunication, internet and information systems
- Energy systems (electricity, hot water, fossil fuel)
- Health service
- Food, drinking water and sewage systems
- Law enforcement, preparedness and emergency service
- Transportation systems
- The highest government of Iceland
- Financial systems

The different types of critical infrastructure are then again highly interdependent. For example, financial systems are heavily reliant on electronic transactions, that both require internet and electricity. Food safety is dependent on transportation systems as much of the food consumed in Iceland is imported. Telecommunication is important for law enforcement, emergency service and transportation. All 8 categories of critical infrastructure depend on computing and data systems, which require both internet/information systems and electricity. Finally, the highest government of Iceland influences all the other systems with their law and policy frames which in return are essential for population, including the government officials. Figure 1 shows the authors´ understanding of how the 8 categories are connected. An arrow pointing from a category to another means that the former is a requirement for the latter to work. An arrow pointing in both directions indicates that two categories are dependent on each other.

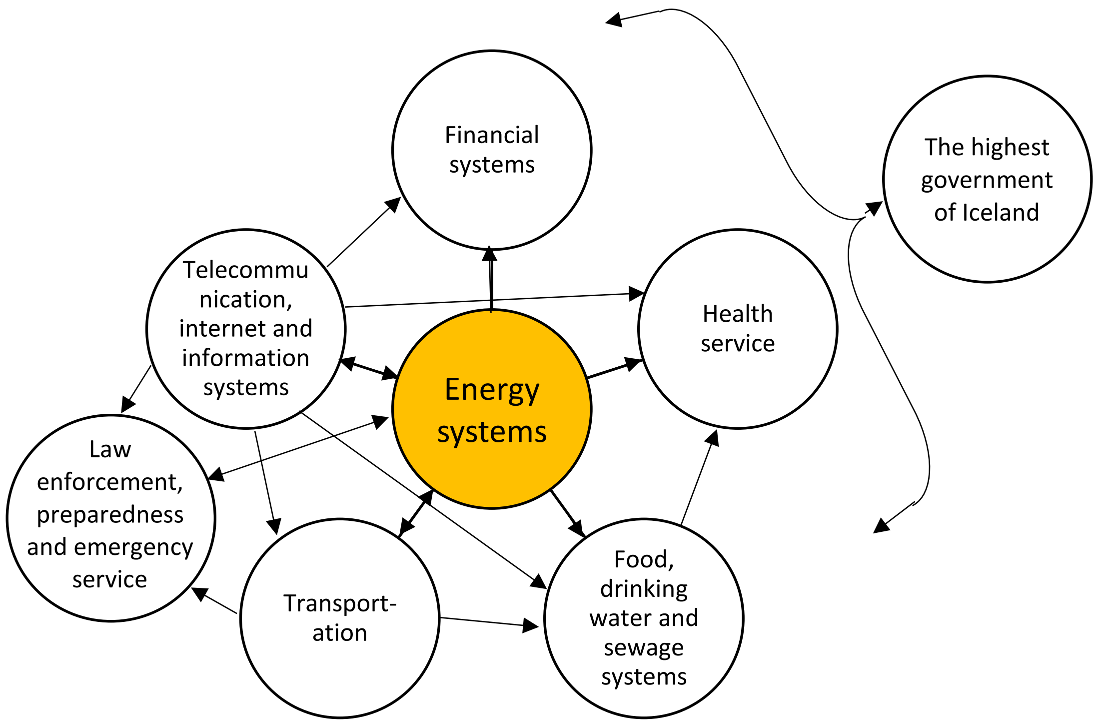

***Figure 1**: Interdependencies of critical infrastructures in Iceland (based on the Icelandic Ministry of Interior, 2015).*

As depicted on figure 1, it can be argued that energy systems along with telecommunication, internet and information systems are the most critical categories of infrastructure, as all the others are dependent on them in some ways. Therefore, it is especially important to protect them from harm and secure their continuous operation. This thesis will focus on energy systems, more specifically the electrical system. The electrical system will here be understood as installations that produce, transmit and distribute electricity to users.

Among threats to the electrical system are natural disasters. In Iceland, those include volcanic threats, as Iceland has several active volcanos. One of them is Öræfajökull, located in south-east Iceland. It has erupted two times since settlement of the country in the 9th century, in 1362 and 1728. Both eruptions were explosive and accompanied by large glacial outburst floods (jökulhlaup). The one in 1362 was particularly extreme and caused vast destruction, loss of life, permanent population displacement and widespread long-term problems (Thorarinsson, 1958). Since the end of 2016, there has been an increased earthquake activity in Öræfajökull which indicates that the volcano is again preparing for eruption (Icelandic Met Office, n.d.). As the surrounding area has both farmlands and popular tourist attractions, many people might be in danger when the volcano starts erupting. The local governments and emergency services are currently working on monitoring and warning systems as well as evacuation plans. However, there is still an uncertainty about how an eruption would affect the complex and highly technical infrastructure. Operators of critical infrastructure, such as electrical systems, need to prepare for the possibility of a large-scale eruption and jökulhlaup in Öræfajökull and try to find ways to secure their continuous operation.

1.2. Objectives

In the pursuit of understanding how the electrical operators should approach this threat the following research question has been formulated:

What critical factors should electrical operators account for in their emergency management for a large-scale volcanic eruption in Öræfajökull?

In this thesis, *critical factors* refer to the principles and organization of the electrical system and emergency management as well as external influences such as characteristics of the volcano. *Electrical operators* are the producers, transmitters and distributers and *a large-scale volcanic eruption* refers to an eruption of similar magnitude and impact as the one in 1362. Finally, *emergency management* is understood as the organization, planning and application of measures to avoid, prepare for, respond to and recover from emergencies (UNDRR & UNGA, 2016).

To help answering the research question, the following 6 sub-questions will be considered.

1. How would a disruption in the electrical system affect the society, close to the volcano and in other parts of Iceland?
2. How vulnerable is the electrical system against a “large-scale eruption” in Öræfajökull?
3. How do electrical operators plan for such an event?
4. How do organizational factors influence the operators´ emergency management?
5. What measures for emergency management are in use?
6. How could the electrical operators improve their emergency management?

The goal of the thesis is to identify factors (principles, organizational factors and external influences) that electrical operators should account for in their emergency management for the specific event “a large-scale volcanic eruption in Öræfajökull”. The 6 sub questions provide guidance in the identification process. They provide an indication of the importance of the electrical system, that is why it is important to search for the factors in the first place, and the reliability and performance of the system. The sub-questions also provide an understanding of the emergency management of the operators, what are the processes and plans, the scope of events and what improvements could be made. The goal of the thesis is not to provide an exhaustive list or detailed guidelines on how electrical operators should handle their emergency management. It is merely intended to emphasize the importance of good emergency management and suggest some important factors to include in that work.

To evaluate the threat that an eruption in Öræfajökull poses to the electrical system, the thesis makes use of existing flooding and ash-distribution models for Öræfajökull and general research of how volcanic activity can affect electrical systems. To then evaluate the electrical operators´ planning and emergency management, the author relies on expert assessments from stakeholders and results from an emergency exercise. By comparing the results to widely accepted theory, the quality of the operators´ emergency management can be assessed and the critical factors defined.

1.3. Limitations and assumptions

The main limitations of the thesis stem from its nature as a master thesis. The thesis was defined and carried out over a period of a few months which limited the scope of data collection and analysis. Therefore, out of all the operators of critical infrastructure and other important functions in society, only electrical operators are considered. Furthermore, the focus is on two operators, the transmitter Landsnet and the distributor RARIK. Other distributors and electrical producers are considered less relevant as an eruption in Öræfajökull would likely affect their systems to a lesser extent. As the assessment of the operators´ emergency management relies heavily on information from the companies´ representatives, the focus of the thesis is also somewhat controlled by who were willing and had the time to attend interviews. The fact that the spokesperson from Landsvirkjun (the main electrical producer) considered the topic not relevant for their company was a factor in the limited focus on electrical producers in the thesis.

Resources were also a limiting factor in the thesis. The work was done by one master student with a background in engineering and societal safety rather than geoscience. Therefore, the geological research that the thesis relies on is accepted without much criticism. The same goes for the information on the electrical system. Overall, the thesis should be viewed as preliminary study of a topic that needs to be researched further for better results.

1.4. Report disposition

The thesis is divided into 7 chapters. After the introduction follows a presentation of the electrical system in Iceland, Öræfajökull volcano and their interaction. Then the analytical terms and theoretical models are introduced. The research methods used in thesis are explained in a separate chapter. After that the findings are presented and the 6 sub-questions are answered. Those are discussed in the next chapter where the critical factors are identified. Finally, the conclusion chapter summarizes results and answers the research question.

2. ÖRÆFAJÖKULL VOLCANO AND THE SYSTEMS INCLUDED IN THE STUDY

This chapter presents the background of the thesis. It introduces the Icelandic electrical system, the volcano Öræfajökull and eruption-related hazards to the electrical system. It summarizes the current knowledge on these topics by discussing findings from existing research. The main studies referred to in this chapter are:

- Potential impacts from tephra fall to electric power systems: a review and mitigation strategies (Wardman et al., 2012): This study summarizes the impact that tephra fallout is known to have on electrical systems in eruptions worldwide since 1980. It discusses the systems sensitivity to tephra and suggest mitigation strategies. Findings in this article will be used to determine how an eruption in Öræfajökull can influence the Icelandic electrical system.
- Volcanogenic floods in Iceland: An assessment of hazards and risks at Öræfajökull and on the Markarfljót outwash plain (Pagneux et al., 2015-a): This study was led by the Icelandic Meteorological Office, on behalf of the national collaborative research program *Gosvá*. It assesses the hazards and risks of jökulhlaups in two areas, Öræfi district and Markarfljót outwash plain, investigates the magnitude and possible impact of such floods and defines areas at risk. The results from this project will be used to describe the expected flooding in a large-scale eruption in Öræfajökull and evaluate its damage on the electrical system.
- Assessing Impact to Infrastructures Due to Tephra Fallout From Öræfajökull Volcano (Iceland) by Using a Scenario-Based Approach and a Numerical Model (Barsotti et al., 2018): This study was conducted in 2018 by researchers from the Icelandic Meteorological Office and the University of Iceland. Based on a scenario similar to the 1362 eruption, it investigates the possible impact of tephra fallout from Öræfajökull on roads, airports and electrical power lines. By running the VOL-CALPUFF dispersal model several times, the ash dispersal in the atmosphere and deposit on the ground is simulated. This is compared to the location and assumed vulnerability of infrastructure. The results from this project will be used to assess the tephra fall in a large-scale eruption in Öræfajökull and its effect on the electrical system.

2.1. The electrical system in Iceland

To understand what the electrical operators should account for in their emergency management, it is first important to get a basic understanding of the electrical system in Iceland. This chapter presents the legal framework around the system and its main components. A special focus is on the area close to Öræfajökull that might be hit by a jökulhlaup and parts that are vulnerable to ashfall.

2.1.1. Introduction

The electrical system can be divided into three parts, production, transmission and distribution. In general, electricity in Iceland is produced by hydro or geothermal powerplants and transmitted to major users and distributors that deliver electricity to general users (the Federation of Icelandic Industries, 2017). Figure 2 shows the basic components of the electrical system, from production to user. Electricity is produced in *1) power plants*. From there the *2) transmission system* transports electricity to *3) major users* and *4) substations* that lower the voltage before it goes to the *5) distribution system*. The distribution system then provides electricity to the *6) general users*, such as homes and companies.

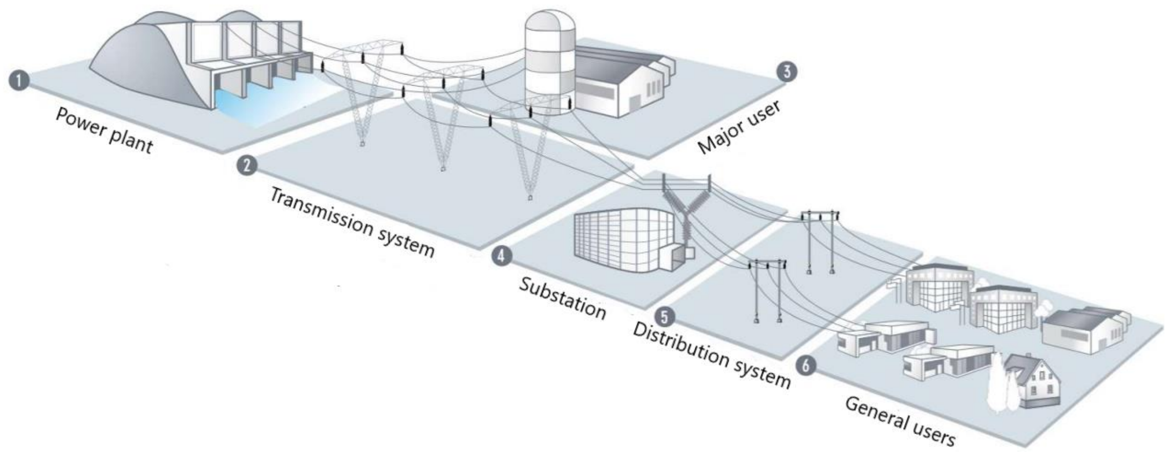

***Figure 2**: The main components of the electrical system in Iceland (modified from Landsnet, n.d.-b)*

2.1.2. Laws and responsibilities of operators

The main legal framework pertaining to the electrical sector in Iceland is the Electricity Act, No. 65/2003. Its goal is to promote an electrical system that is economical and reliable. For that purpose, it is differentiated between production and sale on one hand and transmission and distribution on the other hand. The idea behind this is to have competition on the market in the production and selling part, while the transmission and distribution part is subject to concession with strict official control (Electricity Act).

According to the Electricity Act, producers are supposed to have agreements with transmitters on the amount of energy delivered into the system. The transmitters have corresponding agreements with the major users and distributors, that again have agreements with their users. Should anyone in this chain fail to fulfil their agreements, the companies may be held liable and a compensation demanded. In case of events resulting in shortages in the electrical supply, the transmitter and distributers are required to ration the power to their users, generally applying the equality rule (see Administrative Procedures Act, article 11). In even more severe situations, that are considered “unmanageable”, the users´ right to compensations no longer exists. The Minister of Industry and the National Commissioner will take over and decide who gets power and who not. To minimize the risk of these situations, the electrical producers, transmitters and distributers are, according to the Electricity Act, required to have emergency response plans for known hazards.

2.1.3. Cooperation in the sector

The Electricity Act also presents a consultative emergency preparedness platform called *Neyðarsamstarf raforkukerfisins* (NSR), which the electrical producers, transmitters, distributers, major users and official actors are members of. In English, the name of the platform would be “Iceland’s Electric Grid Emergency Preparedness Forum”. The transmission company Landsnet leads this forum and therefore represents it in communication with other entities such as the Department of Civil Protection during emergencies. However, although the name suggests it, NSR is not a response body but merely a forum for representants from different companies to share their experience, discuss methods and form relationships. NSR regularity hosts meetings, seminars and professional lectures and organizes emergency exercises for the member companies. For example, in February of 2019, NSR hosted an emergency exercise where the scenario was a large eruption in Öræfajökull during a pandemic. Also, NSR is a platform for leading official projects, such as a national risk assessment for the electrical system.

Samorka, the association of the Icelandic electricity industry, district heating, waterworks and sewage utilities in Iceland, also plays an important part in the electrical operators´ cooperation. Various professional groups work within it where experts share their knowledge. On top of that, Samorka regularly hosts common meetings and conferences, organizes professional courses and carries out common projects. Samorka is not as focused on emergency preparedness and management as NSR, rather on normal operation (Samorka, n.d.-b).

In chapters 2.1.4–2.1.6., each part of the electrical system, that is production, transmission and distribution, will be described further with special focus on how an eruption in Öræfajökull might affect it.

2.1.4. Electrical production

Over 99% of all electricity in Iceland is produced by 5 companies, Landsvirkjun (73% in year 2015), Orka náttúrunnar (17,3%), HS Orka (6,9%), Orkusalan (1,4%) and Orkubú Vestfjarða (0,5%) (the Federation of Icelandic Industries, 2017). These companies are subject to general market competition laws and are free to decide their price and which customers to serve (Samorka, n.d.-a). The electrical production in Iceland is almost completely based on renewable energy, hydropower (about 75%) and geothermal (about 25%). Production by wind and fossil fuel count together for less than 1% of the production (the Federation of Icelandic Industries, 2017). The largest power plant, Fljótsdalsstöð, is situated in east Iceland, but apart from that most of the production is in Southwest-Iceland (Orkustofnun, 2017). Figure 3 shows all power plants in Iceland that in 2017 produced more than 100,000 MWh.

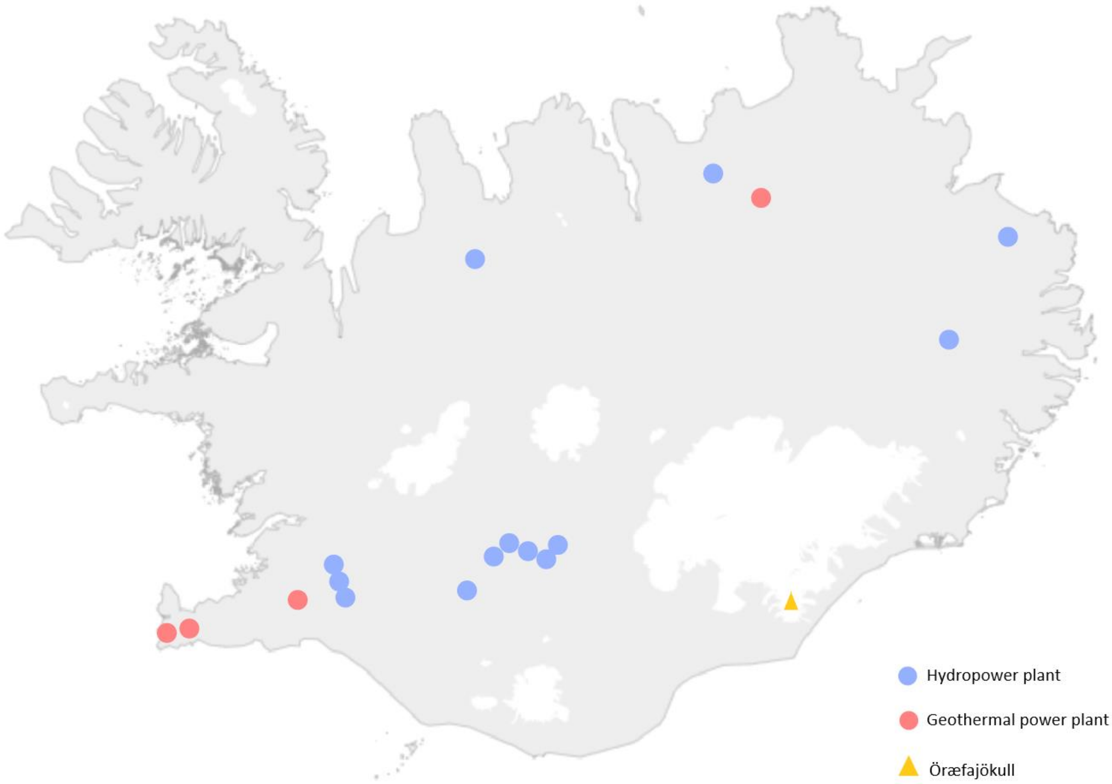

***Figure 3**: Power plants in Iceland producing more than 100,000 MWh in 2017 (based on data from Orkustofnun, 2017).*

Even though almost 70% of Icelandic power plants are in volcanic zones (the Federation of Icelandic Industries, 2017), no power plant is in the area close to Öræfajökull (figure 3). As further depicted on figure 3, power production is not equally distributed throughout the country. Therefore, it is often necessary to transmit electricity long distances with subsequent losses.

2.1.5. Electrical transmission

The company Landsnet is the sole electrical transmitter in Iceland. Its role is to transmit electricity from the power plants to major users, that is big industries, and distribution operators. To minimize losses, the transmission system is run on a high voltage, mostly 66-220 kV. Single 33 kV lines are also in use (Landsnet, 2018). Figure 4 shows Landsnet´s distribution system as it was in 2017.

***Figure 4**: Landnet´s transmission system in 2017 (modified from Landsnet, 2017)*

Landnet´s transmission system is interconnected such that the electricity has at least two possible routes to go and a disruption or damage in one place should not lead to power outages. This type of system is called "N-1 secure". Some areas are excepted from this, e.g. the West fjords. Furthermore, there is only one line all the way from Sigalda to Hryggstekkur in the south and south-east part of the country (see figure 4). Should the line get damaged somewhere on this section, e.g. because of a jökulhlaup or heavy ashfall from Öræfajökull, the electricity from the production sites in Southeast Iceland would have to travel a much longer way to get to East Iceland, clockwise instead of counter-clockwise. This would result in enormous losses and most likely reductions in normal service in the east and northeast part of the country (Landsnet, 2018).

According to a representative of Landsnet that was interviewed, the company has for some years been trying to get permission to strengthen its system by building more lines and changing out some of the old lines for more powerful ones. By increasing the capacity and adding interconnections, this would make the system more robust against volcanic hazards. However, Landsnet´s plans have met substantial resistance from the public and construction has not started as of June 2019. In a report from the Federation of Icelandic Industries (2017) it is pinpointed that finding a solution to this problem is very urgent. The load on the system is gradually increasing while its reliability is decreasing.

The main units in the transmission system are lines, towers, insulators and substations. The electricity is transported via overhead lines or underground cables. The transmission system in Iceland is mainly built up with three-phase overhead lines (three parallel electrical wires), but in recent years some lines have been replaced with underground power cables. This is in accordance with technical improvements and environmental discussions. The overhead lines are supported by towers made from timber or steel. Between the towers and lines there are insulators that prevent conductivity down to the ground, made of porcelain or glass. Finally, substations composed of multiple components regulate the voltage and transfer electricity into or out of the system (Landsnet, n.d.-a).

2.1.6. Electrical distribution

With help of substations, electricity is transferred from Landsnet´s transmission system to the distribution systems, that further distribute it to general users. In Iceland there are 6 electrical distributors, HS Veitur, RARIK, Veitur, Norðurorka, Orkubú Vestfjarða og Rafveita Reyðarfjarðar. The distribution system is run on 0,4 kV to 132 kV (the Federation of Icelandic Industries, 2017).

RARIK is the company that distributes electricity to most parts of Iceland, especially the rural areas. It serves everywhere except for the capital area, the towns Akureyri, Vestmannaeyjar and Reyðarfjörður and the areas Suðurnes, Árborg and Vestfirðir. Approximately 16% of the country´s population receives their electricity from RARIK (RARIK, 2018). Unlike Landsnet´s transmission system, RARIK´s distribution system is not a “N-1 secure” interconnected system. Instead, one disruption can cut off electricity in a defined area.

Figure 5 shows RARIK´s system. According to RARIK´s interviewees, it is divided into 4 sectors (south, east, north and west) that are run relatively independently by the respective site manager. RARIK´s distribution system has roughly the same main units as the transmission system. However, more underground power cables are in use in the distribution system. As shown in figure 5, the distribution system closest to Öræfajökull is entirely composed of underground cables.

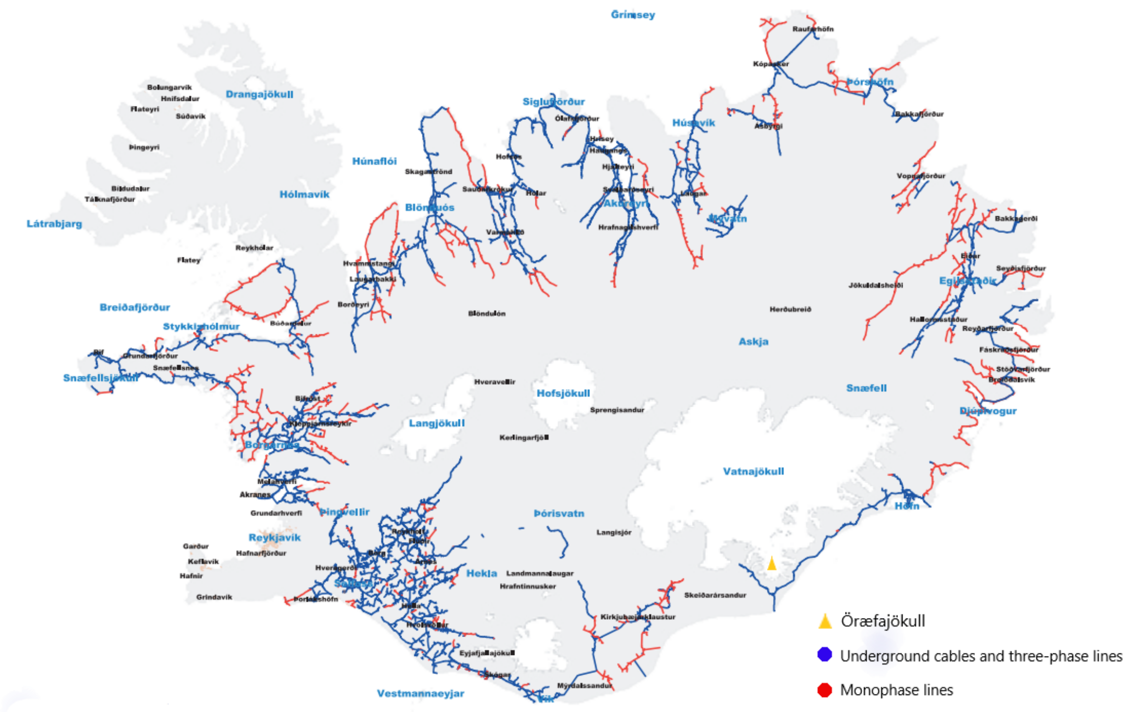

***Figure 5**: RARIK´s distribution system in 2018 (modified from RARIK, 2018)*

2.2. The volcano Öræfajökull

2.2.1. Introduction

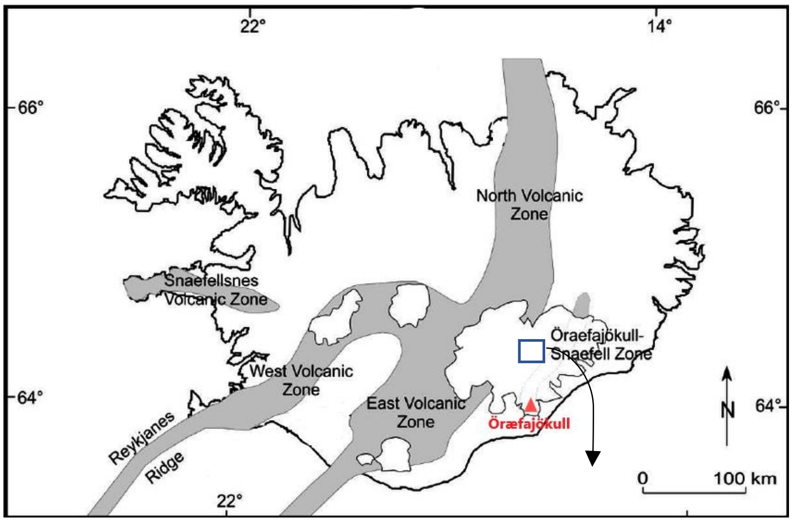

***Figure 6**: Öræfajökull and the main volcanic zones in Iceland (modified from Andrew, 2008)*

Öræfajökull is an active ice-covered stratovolcano, located on the southern margin of Iceland´s largest glacier, Vatnajökull (Thorarinsson, 1958). Its caldera is about 3 km by 4 km and above the rim rises the county´s highest peak, Hvannadalshjúkur at 2110 m, along with other peaks (Barsotti et al., 2018). In general, the main volcanic zones in Iceland are located on the spreading tectonic plate boundaries and over the hot spot. However, as depicted in figure 6, Öræfajökull lies somewhat east of the main volcanic zones (Tweed, 2012).

Since settlement in the 9th century, Öræfajökull has featured two explosive eruptions, in 1362 and 1728. The eruptions have been categorized according to the Volcanic Explosivity Index (VEI) proposed by Chris Newhall and Stephen Self in 1982. It categorizes eruptions depending on the volume of material ejected, the height of the plume and the duration of the eruption. The scale is logarithmic from 0 to 8, where 0 means non-explosive and 8 involves more than 100,000 km^3 of ejected tephra (Newhall and Self, 1982). The index is briefly explained in table 1. The eruption in 1728 was quite small (VEI 4) whereas the 1362 eruption was the largest explosive eruption in Iceland in historical times (Thorarinsson, 1958; Gudmundsson, 2008). It falls into the category VEI 6 and is considered the largest eruption in Europe since Vesuvius destroyed Pompei in 79 AD (Tweed, 2012). The eruption carried on for several months and during that time up to 10 km^3 of freshly fallen tephra was emitted, or about 2 km^3 when converted to dense rock (Thorarinsson, 1958). Pyroclastic density currents and jökulhlaups also accompanied the eruption, destroying the then prosperous district Litla-Hérað and its estimated 30 farms (Gudmundsson et al., 2008). When the district was rebuilt some decades later it got the name Öræfi, whick means “desert” or “wasteland”.

***Table 1**: The Volcanic Explosivity Index (based on Newhall and Self, 1982)*

VEI	**Description**	**Volume ejected [km^3]**
m0	Non-explosive	< 0,00001
1	Small	0,00001 – 0,001
2	Moderate	0,001 – 0,01
3	Mod-large	0,01 – 0,1
4	Large	0,1 – 1
5	Very large	1 – 10
6		10 – 100
7		100 – 1000
8		> 1000

Since September 2017, increased unrest has been observed in Öræfajökull volcano. This involves growing seismicity, gas release and the formation of a cauldron in the middle of the caldera (Barsotti et al., 2018). Accordingly, there has been increased emphasis on monitoring, research and preparation for a possible eruption.

Volcanic eruptions have multi-hazard characteristics. Tephra falls, pyroclastic density currents (PDC), lava flows, lahars and jökulhlaup have different spatial and temporal scales. In the case of Öræfajökull, the two most prominent hazards are glacial outburst floods (jökulhlaup) and tephra fallout. Those will be covered in the next two chapters.

2.2.2. Jökulhlaups (glacial outburst floods)

One of the main volcanogenic hazards in Iceland are glacial outburst floods, or jökulhlaups. They occur when hot freshly erupted lava, tephra, hot gases or geothermal heat interacts with glacier ice and snow (Pagneux et al., 2015-b). This interaction results in massive floods of water, ice and sediment mixed together (Helgadottir et al., 2015).

Jökulhlaups pose the highest risk to human lives when they occur on populated slopes of large, steep-sided, ice-covered volcanos. In Iceland, those situations are found in the slopes of three glaciers, Öræfajökull, Eyjafjallajökull and Snæfellsjökull (Pagneux et al., 2015-b). For infrastructure as well as living organisms it can be assumed that a jökulhlaup will destroy everything in its path, washing away both overhead electrical power lines and underground cables.

Volcanic jökulhlaups from Öræfajökull can be categorised in three types, depending on the source (figure 7).

A. Floods resulting from eruptions in the caldera. The ice there is up to 500 m thick so large eruptions could cause heavy flooding, up to 100,000 m^3/s. This type of jökulhlaup would most likely flow down Virkisjökull and Falljökull or Kvíarjökull (location shown on figure 8).
B. Floods resulting from fissure eruptions on the upper flanks. There the ice is 50-100 m thick and expected size of floods on the range 1000-10,000 m^3/s. This type of jökulhlaup could occur anywhere on the slopes between Virkisjökull and Hrútárjökull.

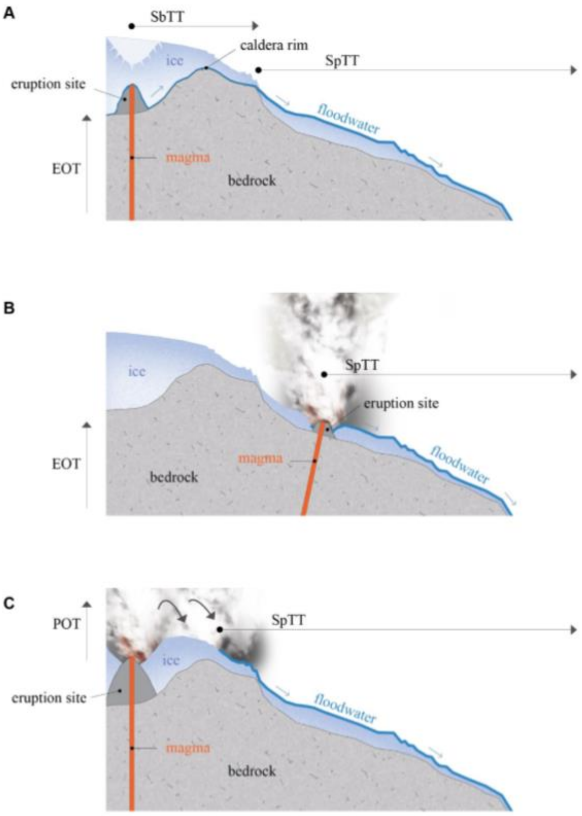

Figure 7: *Three types of jökulhlaups. A: caldera eruptions, B: flank eruptions and C: formation of PDC. Abbreviates stand for the following. EOT: eruption onset time, SpTT: transport time at onset of subglacial flow, POT: onset time of PDC (Pagneux, 2015).*

C. Floods resulting from hot (300-600°C) pyroclastic density currents (PDC). This could happen in large explosive eruptions, of similar magnitude as the one in 1362. The expected size of floods is 1000-20,000 m^3/s and they could occur anywhere on the slopes between Svínafellsjökull and Hrútárjökull (Helgadottir et al., 2015).

Figure 8 shows the outlet glaciers mentioned in the text above.

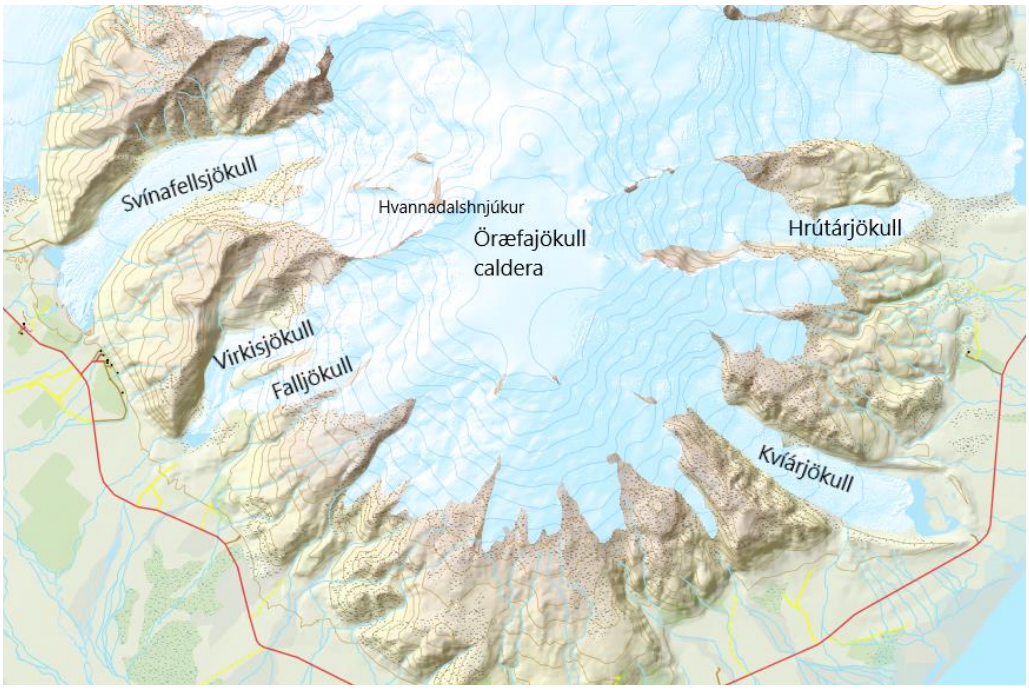

Figure 8*: Öræfajökull and its main outlet glaciers (based on data from the National Land Survey of Iceland).*

In the paper *Öræfajökull Volcano: Numerical simulations of eruption-induced jökulhlaups using the SAMOS flow model*, Helgadottir et al. (2015) assess the expected flooding area around Öræfajökull in the case of a subglacial eruption. The assessment is based on ten different melting scenarios that Gudmundsson et al. (2015) define in their paper. Superimpositions of these scenarios indicate that a total area of 347 km^2 is at risk of flooding (figure 9). Of that area 284 km^2 (82%) are exposed to all three types of flooding, 42 km^2

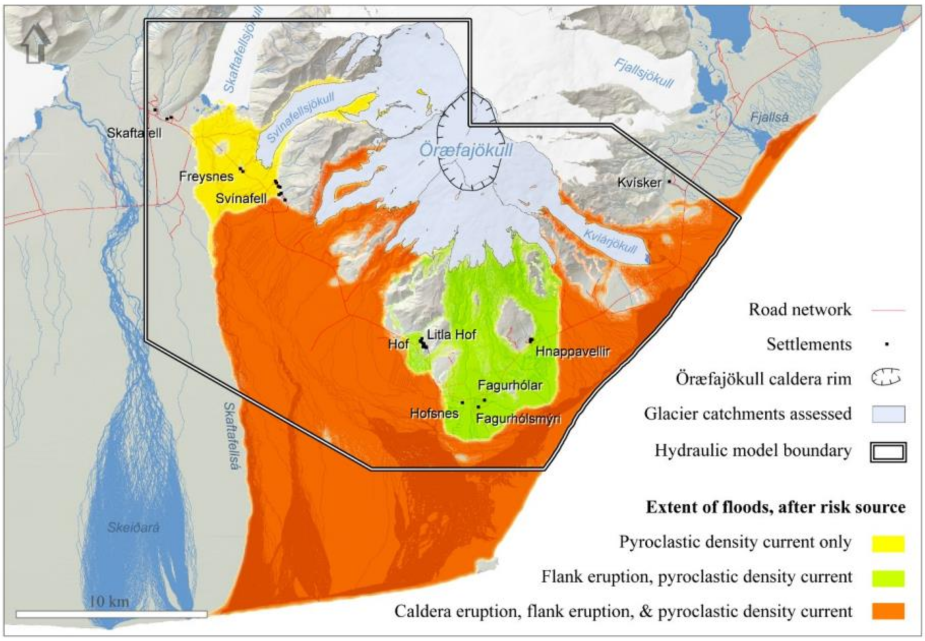

Figure 9: *Areas at risk for the different types of flooding (Helgadottir et al., 2015).*

(12%) are only exposed to type B and C and 21 km^2 (6%) are only exposed to type C (Helgadottir et al., 2015).

The time available for evacuation of the affected areas depends on early indications and warnings as well as the eruption´s type and location. According to modelling (Pagneux, 2015), the floods can reach the main road in the region only 20-30 minutes after the start of an eruption in the caldera or on its flanks and 15-25 minutes after the onset of a pyroclastic density current. On the other hand, it is estimated that the evacuation of people from the affected area would take at least 30-35 minutes. Therefore, early warnings are extremely important. If an eruption would occur without warning and prior evacuation, it is assessed that up to 130 people could be in severe danger and potentially lose their lives. 240-250 more would get isolated due to destruction of parts of the main road (Pagneux, 2015).

It can be assumed that all infrastructure hit by a jökulhlaup will get wiped away. This applies to roads, airstrips, buildings, and communications and electrical installations alike. The use of underground power cables rather than overhead lines will minimize the risk of disruption due to tephra fallout, but even underground cables will unlikely withstand the power of jökulhlaups.

2.2.3. Tephra fallout

Tephra is the fine-grained product of explosive volcanic eruptions, composed of rock, minerals and glass. The finest tephra (<2 mm in diameter) is often called volcanic ash (Wardman et al., 2012). Volcanic ash can be dispersed large distances by wind, making it the most widespread eruption product. Therefore, it tends to cause problems far away from the eruption site. Although tephra fall rarely poses an acute threat to human life, it can have severe impact on the society by e.g. causing health issues and disruption of critical infrastructure and food production (Wilson et al., 2012). Simulations indicate that an eruption similar to the one in 1362 would lead to tephra fallout in most parts of Iceland, depending on the wind direction. The magnitude is controlled by the proximity to the volcano, wind direction and the material´s grain size. Because of dominant westerly winds, the likelihood of heavy tephra fallout is higher in the eastern part of the country (Barsotti et al., 2018).

As Barsotti et al. (2018) summarize in their paper, tephra can cause various issues such as health issues, roofs/building collapse, poor visibility, dangerous road conditions, contamination of water reservoirs and vegetation, telecommunication disruption, transportation system disruptions and damage to electrical infrastructure.

These issues are affected by the location of the volcano, the tephra´s composition and grain size distribution and weather factors such as humidity and wind (Wilson et al., 2012). For electrical systems, the main problems that tephra fallout can cause are:

Insulator flashover: Insulator flashover is the most common problem that ashfall poses to the electrical network (Wilson et al., 2012). It refers to an unintended electrical discharge around the insulators that may result in line fault and electric outage. This can occur at the production site, in transmission lines or distribution lines. Insulator flashover can occur due to accumulation of highly conductive tephra or volcanic ash on the power lines. The flashover risk is controlled by the amount of tephra adhering to the lines and its conductivity, that is the tephra´s moisture content, soluble salt content, compaction and grainsize as well as the insulator size, composition, orientation and condition (Wardman et al., 2012).

Weather factors play an important role in the flashover risk. Dry tephra is not conductive except in humid condition, such as light rain, fog or mist. Water mobilizes readily soluble salts that reduce the tephra´s resistivity, increasing the flashover risk (Wilson et at., 2012). This may initiate a leakage current across the insulator´s surface, resulting in flashover if a high enough current is achieved. This may furthermore lead to disruption in service or power outages (Wardman et al., 2012). If, however, the rain is heavy or the wind strong, the weather might manage to remove the tephra from the power lines (Wilson et al., 2012).

Physical damage to lines, tower or poles: Like jökulhlaups and lava flows, tephra falls can cause physical damage to electric installations. This occurs when the load of tephra adhering to lines or sitting on other structures gets too great. The likelihood of breakage is highest in wet or humid conditions with heavy tephra fall (>10 mm). In addition, grain size matters, as fine-grained tephra is more likely to adhere to structures that coarse material (Wilson et al., 2012).

Abrasion and corrosion of equipment: Due to its hardness and sharp edges, tephra can be highly abrasive. When tephra gets into equipment, especially moving parts, it can accelerate normal wear considerably. At hydrological power stations, suspension of ash in reservoirs can lead to abrasion of turbines. Ash can also damage wind turbines and cooling fans on power transformers (Wardman et al., 2012).

Controlled shutdown during clean-up: When ash is being cleaned off equipment, it can be beneficial to turn off electricity at vulnerable nodes, e.g. generation facilities and substations. Such controlled outages are sometimes also used during heavy tephra fall to prevent abrasion of moving parts (Wardman et al., 2012).

Disruption of generation facilities and substations: At electric generation sites and substations, tephra can block air intakes for turbines, ventilation, heating and cooling systems. Volcanic ash that penetrates buildings can furthermore damage sensitive machinery and electronics. This can lead to reduced efficiency, precautionary shutdown, damage or failure.

To estimate the impact that tephra fallout from Öræfajökull would have on electrical infrastructure, it is natural to start with looking at probable dispersal and disposition of tephra. The simulations run by Barsotti et al. (2018) are based on the eruption in 1362. They are supposed to represent a high-impact but low-probability scenario. The simulations are used to create probabilistic hazard maps, representing the dispersal and disposition of tephra as a spatial probability. Potential impact on critical infrastructure is then assessed by comparing the hazard maps to the location of infrastructure and their assumed critical values for disruption.

According to the simulations, the severe impact of tephra fallout on power lines is confined to the area closest to Öræfajökull. The failure threshold used was 100 mm of ash, based on the study of Wilson et al. (2012) that e.g. reported high likelihood of insulator flashover with wet ash over 5 mm and medium likelihood of equipment breakage with dry ash over 100 mm. The simulations indicate that there is >75% probability that 115 km of Landsnet´s transmission line will be exposed to such load. If we look at the zone with more than 50% probability of such load, the length of transmission line failing is over 160 km (Barsotti et al., 2018). Figure 10 shows the impact map. In the assessment of Barsotti et al. (2018) only the transmission system is taken into consideration. That is also the system at most risk, as the production sites are further away from the volcano and the distribution system closest to the volcano is underground.

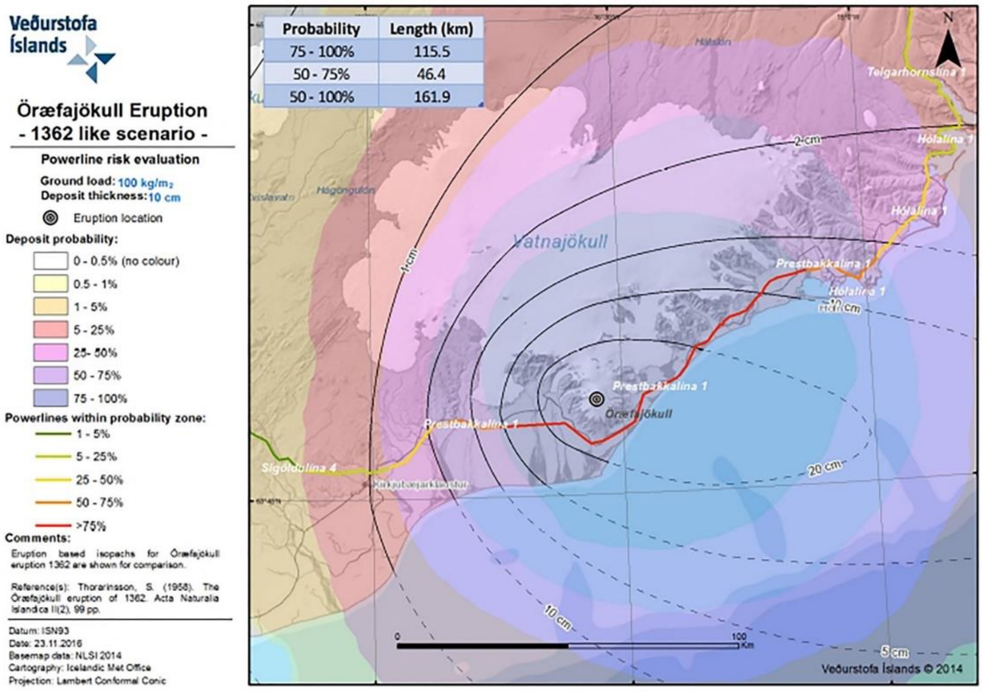

__Figure 10__: Potential tephra fallout impact to power lines (Barsotti et al., 2018).

3. ANALYTICAL TERMS AND THEORETICAL MODELS

This chapter presents the theoretical structure of the thesis. It defines and discusses central terms and presents theory on emergency management that will be used to help defining the critical factors that the electrical operators should account for in their emergency management.

3.1. Uncertainty

Chapter 2 presented possible eruption scenarios and different consequences that an eruption could have for the electrical system. In that discussion as well as in general preparation for an eruption in Öræfajökull, a lot of uncertainty is involved. Among other things, there is uncertainty about the timing, magnitude and characteristics of an eruption in Öræfajökull, the weather at the time and the affects that it might have on the electrical system and the society.

People´s understanding of uncertainty is dependent on scientific discipline and the nature and goal of the task worked on. Mathematicians, economists, politicians and philosophers have different approaches to uncertainty, which may be natural as their tasks and goals are varied. In this thesis, the approach is planning and decision making for an unknown future. In that approach, there is uncertainty regarding geological factors (the volcanic behavior), technical factors (the electrical system) and human factors (the emergency preparedness and response).

There are various sources of uncertainties in systems. Below some of these are explained further (based on Norwegian Directorate for Civil Protection, 2014; Aven, 2006; Njå, Solberg & Braut, 2017):

Aleatory uncertainty or statistical variation refers to the uncertainty about how relevant the data is for the system that is being analyzed. This type of uncertainty is sometimes expressed with confidence intervals, where a larger interval means more uncertainty. In this there, there is e.g. aleatory uncertainty related to the relevance of using a 1362-like eruption in Öræfajökull as a design event for the electrical operators´ emergency management. This will be discussed further in chapter 3.3.

*Epistemic uncertaint*y refers to uncertainty due to lack of knowledge. This type of uncertainty is related to lack of data and expert’s incomplete understanding of the phenomenon studied.

In this thesis, this is for example related to the volcanic behavior of Öræfajökull and the assessment of the system´s sensitivity to ashfall. Epistemic uncertainty can sometimes be reduced by gathering more data and studying the phenomenon better. This will be further discussed in chapters 6.

Model uncertainty is related to the appropriateness of methods to assess the risk, hazard or vulnerability. The uncertainties lie in how well the models used represent reality. This type of uncertainty is discussed in chapter 4.

These different types of uncertainty then mix together. E.g., input data in models are based on expert assessment (where there is epistemic uncertainty about the level of understanding) and data from past eruptions (where there is aleatory uncertainty about the relevance of that data for future eruptions).

Njå, Solberg and Braut (2017) argue that uncertainty has a different meaning depending on the time concept. Uncertainty in the past refers to a methodological challenge related to what has been observed and comprehended. Uncertainty in the presence is purely epistemic and can be reduced by gathering more data and improving the knowledge on the phenomenon. Finally, uncertainty in the future cannot be reduced as the future will always be unknown. To help with planning and decision making for an unknown future, the best way of handling uncertainty is to highlight prerequisites, assumptions, models and data that today´s analysis use to express the predictions about the future.

3.2. Emergency and emergency management

Uncertainty is also important when discussing emergencies, crises or disasters. These terms all have similar meanings but are often seen as differently severe or large. However, sometimes they are used interchangeably. The Norwegian Directorate for Civil Protection (DSB) defines *crisis* as: “an unwanted situation involving a high degree of uncertainty and potentially unacceptable consequences for individuals, organizations or states affected” (Norwegian Directorate for Civil Protection, 2014). In this thesis the term *emergency* is used instead of crisis and applies to the adverse event “a large-scale eruption in Öræfajökull”. *Emergency management* is furthermore understood as the organization, planning and application of measures to avoid, prepare for, respond to and recover from emergencies (UNDRR & UNGA, 2016). Among the important factors in emergency management are risk identification and risk reduction (see more details in chapter 3.5.3.) and therefore one´s understanding of the risk has a big influence on the management.

3.3. The definition of a "large-scale eruption"

This thesis investigates the electrical operators´ emergency management for a "large-scale eruption" in Öræfajökull. However, as there have only been two eruptions in Öræfajökull since the settlement of Iceland it may seem unrealistic to define a "large-scale eruption" based on one of those two events. For this volcano, it is nevertheless considered acceptable. The 1362 eruption is assessed to have emitted about 10 km^3 of tephra, making it a Volcanic Explosivity Index (VEI) 6 category event. Out of hundreds of eruptions in Iceland since settlement, this is the only VEI 6 eruption (Gudmundsson et al., 2008). Therefore, it is considered acceptable to look at a 1362-like event as a "large-scale eruption" in Öræfajökull or a "worst-case scenario" that still is plausible. For this reason, the ashfall and flooding models presented in chapter 2 are assumed to represent the event of interest, the "large-scale eruption" that the research question addresses.

3.4. Vulnerability and robustness

One of the sub-questions in this thesis is about the electrical system´s vulnerability against a large-scale eruption in Öræfajökull. *Vulnerability* can be understood as a systems tendency to suffer damage due to external events (WHO & EHA, 2002). In this thesis, the vulnerability discussed is therefore the electrical system´s tendency to suffer damage due to a large-scale volcanic eruption in Öræfajökull. Vulnerability is often evaluated parallel to *robustness* and is then viewed as its opposite (Engen et al., 2016). In that understanding, a system´s condition lies on a scale from vulnerable to robust where the robustness can be increased by planning and preparing for the adverse event and strengthen the system against it. Therefore, in this thesis, the system´s vulnerability and robustness are assessed simultaneously. This is done by investigating how an eruption can cause problems for the electrical system and review what measures or lack of what measures make it likely or unlikely that it will.

3.5. Emergency management

3.5.1. The process of emergency management

As stated, emergency management is in this thesis understood as the organization, planning and application of measures to avoid, prepare for, respond to and recover from emergencies (UNDRR & UNGA, 2016). An important aspect of emergency management is that conditions, technologies and resources change over time. (Perry & Lindell, 2003; Rake & Sommer, 2017; Engen et al., 2016). Therefore, the emergency management process is often depicted as a linear circular process containing different phases that need to be executed, reviewed and updated regularly (figure 11). The Federal Emergency Management Agency (FEMA) in the USA divides emergency management into four phases: mitigation, preparedness, response and recovery (FEMA, n.d.). Those phases are in line with the definition of emergency management where activities are undertaken to avoid (mitigate), prepare for, respond to and recover from emergencies.

The process used in this thesis has one more phase, situation assessment, that focuses on understanding the existing hazards and risks and deciding on which of them to prepare for. This is in accordance with processes suggested by Aven et al. (2004), Engen et al (2016) and Rake and Sommer (2017) where some form of mapping, assessment or analysis plays an important role. The main goal of this phase is to define the emergencies that the later phases focus on mitigating, preparing for, responding to and recovering from and understand their causes.

It should be emphasized that a linear understanding of the emergency management process is a simplification, and in reality, different phases are often being worked on and updated simultaneously (Perry & Lindell, 2003). All the same, such a depiction is considered suitable in this thesis, as it gives a simple and neat overview of the phases. Figure 11 shows the emergency management process used in this thesis. It is based mainly on the process of FEMA (n.d.) with additions from Aven et al. (2004), Engel et al. (2016) and Rake & Sommer (2017).

The different phases cover the following:

Situation assessment: The first step is to identify hazards and risk by investigating what can go wrong, why and how. Tools for this are e.g. information gathering, hazard assessment, risk assessments and analysis and vulnerability assessments. After that, unwanted events or emergencies to prepare for can be defined.

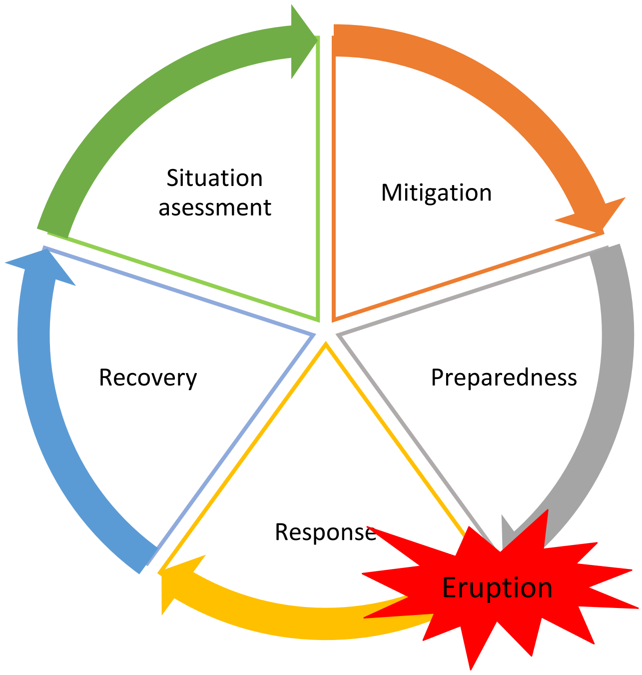

Figure 11*: The emergency management process.*

Mitigation involves taking sustained actions that reduce or eliminate the probability or consequences of the unwanted events. The goal is to protect people and structure and reduce the cost of response and recovery. The four main strategies mitigation are 1) avoiding any exposure to the risk, 2) applying measures to reduce the probability or the severity of an event 3) transferring the risk by handing it off to a third party and 4) accepting the risk because the cost of risk mitigation is so great that it outweighs the potential loss.

Preparedness: It is not possible to remove all hazards and eliminate all risk. Therefore, good preparedness that reduces the impact of the residual hazards and risk that they pose is important. Preparedness includes developing emergency response plans and procedures, recruiting and training qualified staff, identifying resources that may be required in an emergency, investing in useful equipment and training for emergency response.

Response begins when an emergency is imminent or immediately after it begins. It includes all activities done to save lives and reduce damage from the event. If the preparedness is good, response basically involves taking the emergency response plan in use. Important tasks are to provide emergency assistance to victims, restore critical infrastructure, ensure the continuity of critical services and more.

Recovery involves returning the system and operation to normal. As an example, short-term recovery is about restoring power service while long-term recovery includes repairing and rebuilding structures. When rebuilding it should be a goal to “build back better”, that is use the opportunity to increase the system´s robustness and reduce the probability that a similar emergency will happen again.

The model above is chosen because its phases are simple and general, and it can be applied to different emergencies. It describes the most important tasks of the emergency management rather than stating exactly how they should be done. This approach is influenced by an emergency management guideline proposed by Perry and Lindell (2003) that involves flexibility, a holistic approach and general plans and procedures.

The importance of flexibility (Perry & Lindell, 2003; Engel et al., 2016): This guideline emphasizes the importance of a flexible approach in emergency management. To be applicable to different events and scenarios and allow for adjustments according to situations, an emergency response plan should be general and simple. If need for more detailed description, supporting documents and procedures should be used rather than having the main plan detailed (Perry & Lindell, 2003; Engel et al., 2016). In other words, actors must organize their management is such a way that they have the freedom and capability to adapt to new situations and scenarios.

The phases in the emergency management process in figure 11 refer to activities that either are done before the unwanted event or during and after it. The first three phases, which refer to activities done before the event, can collectively be called planning while the other two can collectively be called execution.

3.5.2. Organizational factors

Quarantelli (1988) emphasizes that good emergency planning does not necessarily lead to good emergency management. Problems that frequently arise are related to communication and information flow, the exercise of authority and coordination. However, the author of this thesis believes that these problems can to some degree be avoided by a good organization of the actors involved and their effective cooperation.

Emergency management in Iceland, Norway and many other countries is based on four fundamental principles about the organization of authority and roles of different actors. They are supposed to promote effective response, cooperation and coordination. The principles are following (Icelandic Ministry of Interior, 2015; Norwegian Mistry of Health and Care Service, 2014):

Responsibility: The actor that normally is responsible for a specific task or sector in society is also responsible for emergency preparation and response in that sector.

Equivalency: The organization or structure established in emergencies should be as similar as possible to the normal operational organization.

Subsidiarity: The emergency should be managed at the lowest possible level, e.g. by the affected company if possible or local government.

Cooperation: All actors have an independent responsibility to coordinate their preparation, response and emergency management with other relevant actors.

These principles can help preventing or reducing the problems that Quarantelli identified. In addition, the following guideline for emergency management is considered relevant:

Cooperation between actors: Perry (1991) states that the success of the emergency response depends on good cooperation between different response actors. Actors must have a mutual understanding of each other's responsibilities, capacity and resources. Their emergency response plans should be coordinated, and they should train together to exercise their cooperation and communication (Perry & Lindell, 2003; Engel et al., 2016).

3.5.3. Measures

Both in the planning and execution part of risk management, measures that influence risks, vulnerabilities, probabilities and consequences have a central role. They are often sorted into technical measures, organizational measures and operational measures (Aven et al., 2004).

Technical measures are composed of structures, equipment or other physical things that either reduce the system´s vulnerability or the probability or consequence of an unwanted event. Examples of technical measures are ash-cleaning equipment and emergency generators.

Organizational measures are related to the company´s organization. Examples of those are manpower, knowledge, exercises, division of responsibility and cooperation with other actors.

Operational measures concern the operation of the system. Examples of those are procedures for monitoring, repairing and responding to problems.

Depending on whether the measures are relevant before or after the onset of an emergency, they are called proactive or reactive (Reason, 1997). Effective emergency management requires use of both types.

4. RESEARCH METHODS

This chapter presents the research methods used in the thesis. It explains how data was gathered, coded and analyzed and discusses the method´s strengths and weaknesses. The goal of the thesis was to define critical factors that electrical operators should account for in their emergency management for a large-scale volcanic eruption in Öræfajökull. In that quest, 6 sub-questions were defined. This chapter explains the process behind answering those questions. Finally, the methods reliability and validity are discussed.

4.1. The sub-questions relevance for the thesis

To recap, the sub-questions were following:

1. How would a disruption in the electrical system affect the society, close to the volcano and in other parts of Iceland?
2. How vulnerable is the electrical system against a "large-scale eruption" in Öræfajökull?
3. How do electrical operators plan for such an event?
4. How do organizational factors influence the operators´ emergency management?
5. What measures for emergency management are in use?
6. How could the electrical operators improve their emergency management?

The questions were intended to help answering the research question: "What critical factors should electrical operators account for in their emergency management for a large-scale volcanic eruption in Öræfajökull?" The critical factors are understood as principles and organization of the electrical system and the emergency management as well as external influences. Here below each question´s contribution to the search of the critical factors is explained.

<u>Question 1</u> addresses the very purpose of this thesis. Its objective was to give an indication of the importance of good emergency management in the electrical sector and confirm if and why it is of value to search for the critical factors.

<u>Question 2</u> contributes to the situation assessment. What situations and strains must the system be able to withstand and how does it perform? This, added to the answer of question 1, was supposed to give an indication of the severity of the emergency that the electrical

operators must prepare for. Vulnerabilities found in the system and situations that might trigger problems are among the critical factors that the thesis strives to identify.

Question 3 investigates the operators’ current state of emergency planning, which is defined as an important part of the emergency management. As there has not been an eruption in Öræfajökull since Iceland was electrified, the operators´ response and recovery were also evaluated based their planning and exercises. The hope was that comparing results from this question with the theoretical model presented in chapter 3.5.1 would help identifying critical factors for the emergency management process.

Question 4 touches on another important part of emergency management, namely organization. It was supposed to help identifying organizational factors that influence the emergency management, and how they should be to promote the best results. The plan was to evaluate the actors´ organization by comparing it to principles presented in chapter 3.5.2.

Question 5 was supposed to highlight the proactive and reactive measures that the operators use in their emergency management. This question is very connected to question 2 as it addresses measures to deal with vulnerabilities found there.

Question 6 was meant to sum up what, based on the findings, the operators could do to improve their emergency management.

After going through these 6 questions, the goal was to have identified the critical factors that already are included in the operators´ emergency management as well as factors that would be beneficial for them to add.

4.2. Research process

The research design is a combination of three types of qualitative methods: literature review, semi structured interviews with key actors and observation of an emergency exercise in the electrical sector. Both primary and secondary data were used. Primary data refers to the interviews and observation, where the researcher was in direct contact with the source of information. Secondary data, on the other hand, refers to the literature, that is scientific papers, risk assessments, emergency response plans and other documents, where data was collected by others. When possible, data gathering and analysis were done simultaneously. This technique promotes that the data gathering is focused on the things needed for the analysis. All data was coded according to which sub-question it belonged to, and that in the end helped answering them.

The different tasks in the research process can be places on a timeline (figure 12):

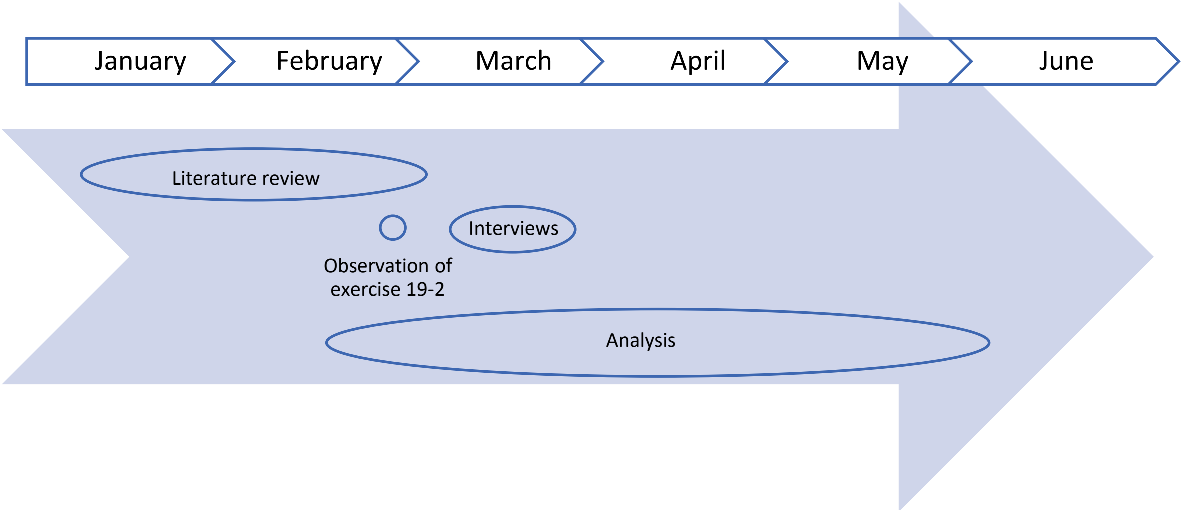

***Figure 12**: The research process.*

4.3. Data gathering

4.3.1. Literature review

The first step in the data gathering was to become acquainted with existing literature on the topic, that is research on the electrical system´s vulnerability to volcanic activity, the volcanic activity in Öræfajökull and other systems´ dependency on electricity. Chapter 1 and 2 present some of that information. The main literature used were scientific papers on Öræfajökull and volcanic hazards in general (presented in chapter 2), a national risk assessment for Iceland (Icelandic Ministry of Foreign Affairs, 2009), Iceland´s official policy in civil protection, safety and security (Icelandic Ministry of Interior, 2015) and emergency response plans from Landsnet and RARIK that were provided in the interviews.

The literature review was essential to provide a broad understanding of the topic and to verify information acquired in the interviews. In contributed specially to answering questions 1 and 2. However, the author found less relevant literature than expected, e.g. no detailed assessments or analysis on how an eruption in Öræfajökull could affect critical infrastructure. In this thesis, literature was therefore mostly used for background information and context.

For answering the research question, the author relied more on the observation and the interviews.

4.3.2. Observation

The second mean of data gathering was observing an emergency exercise in the electrical sector. On 28th of February 2019, a comprehensive emergency exercise called “exercise 19-2” was held. Landsnet on behalf of NSR was the main organizer with the assistance of Verkis consulting engineers. The theme was a large-scale eruption in Öræfajökull accompanied by a widespread jökulhlaup and ashfall all over Iceland. The event was supposed to take place during a severe epidemic, so the participating actors had minimum manpower.

The author, on behalf of Verkis consulting engineers, helped organizing the exercise as well as processing the results. It served as an imaginary “performance assessment” of the electrical operators´ preparedness, response and cooperation, as this was a desktop exercise with real-time communication and decision making but no “boots on the ground” taking physical actions. In preparation of the exercise, organizers and participants pondered over where and how an eruption in Öræfajökull could affect critical infrastructure systems.

Participants were members of NSR as well as response bodies, companies and institutions in the capital area and South-Iceland. Those are the local police, the National Commissioner´s Department of Civil Protection and Emergency Management, health institutions, the Icelandic Meteorological Office and the Icelandic Road and Coastal Administration. As in reality, participants were each based in their own headquarters and communicated through TETRA radio, phone and e-mail as well as the online collaboration tool Workplace. The imaginary event was based on the disastrous eruption in 1362 and the most destructive of the flooding scenarios that Gudmundsson et al. (2015) predicted in their analysis. Furthermore, the wind was said to come from south-east, causing tephra to quickly spread all over Iceland.

During the exercise, the author sat with the exercise organizers and followed up on the proceedings on Workplace and by listening to radio communication. As the researcher was not a participant in the exercise, this was a passive participant observation. After the exercise, there was a phone-meeting for debriefing will all participants. In addition, participants were asked to send an e-mail to the organizers with their experience of the exercise, their “actions” and comments.

The exercise and its preparation contributed to answering all the sub-questions. It emphasized the society´s dependency on electricity by drawing out what "disruptions" short-term electrical outages caused. It helped answering sub-question 2 by providing the author with information about the electrical system´s vulnerability against a large-scale eruption in Öræfajökull. It also gave an indication of the operators´ preparedness (sub-question 3) as the participants reported how they were "responding" to problems and in some cases what plans or procedures they were following. That also revealed some of the measures used (sub-question 5). In addition, the participants organization of authority, decision making and communication could be studied (question 4). Finally, the exercise provided interviewees spoken with after the exercise with updated information on their preparedness status.

The main strength of this observation as a data gathering method was that it served as a kind of performance assessment and revealed some improvement potentials. However, a desktop exercise can never give an accurate picture of the response in real events. In the exercise, there were little "real" actions and instead everyone sat ready looking at the screen and listening to the radio. "Damages" and "disruptions" reported in the exercise were based on what organizers and participants though would happen in the hypothetical scenario and therefore cannot be used to confirm information from the literature. After all, people´s beliefs about the damage and disruptions are largely based on this same literature.

4.3.3. Interviews

For a better understanding of the electrical system, vulnerability to volcanic activity and the operators´ emergency management, central employees of Landsnet and RARIK were interviewed. Two meeting were held, one with Landsnet´s safety manager and the other with RARIK´s safety manager and the director of operations, who also is chairman of the company´s emergency response team. The author also made an unsuccessful attempt to get an interview with representants from Landsvirkjun. Their spokesperson however did not consider their business relevant for the thesis as an eruption in Öræfajökull would have little to no effect on their operation.

The interviewees from RARIK and Landsnet were chosen because of their job titles, and because in preparation of exercise 19-2 it became clear that they had knowledge of the emergency organization in their company and NSR. In preparation of the exercise, they had also participated in evaluating the threat that volcanic activity in Öræfajökull poses on the electrical system and possible consequences should there be disruption. The interviews were semi-structural, that is flexible and conversational but supported by an interview guide with pre-determined questions (interview guide is in appendix 1). The interview guide helped securing that all desired topics were covered and provided the researcher with simple and precise but also open questions when needed. Potential follow-up questions were in some cases included. The interviews were flexible, so the interviewees could focus the discussion on the topics they found most important and the researcher could ask for more details on new information.

By gathering and analyzing the data simultaneously the interview´s utility was maximized. They could be adapted to new information and relevant follow-up questions could be asked. Also, the second interview could ask about things that went missing in the first interview. This however caused the interview guide to change between interviews, which might affect its validity. With the participants´ permission, the interviews were recorded and written notes taken. After each interview, the vocal data was transcribed, making the coding and analyzing processes easier.

The interviews were thorough and contributed to the answers of all the sub-questions. They provided information on Landnet´s and RARIK´s emergency planning and management as well as possible causes and consequences of disruption in the electric transmission and distribution due to an eruption in Öræfajökull. They also provided an opportunity to clarify and deepen the researcher´s understanding of factors from the literature and exercise. In the interviews, selected emergency response plans from the companies were provided.

A limitation of the interviews as a data gathering method is that all the interviewees work for electrical companies, so their information might be affected by their interest to show the operators in a reliable light. However, it is also in their interest to enhance the preparedness. This factor, along with the interviewees´ appearance of honesty and desire for improvements justifies the assumption that their information is according to their best believes.

The fact that the interviews were thorough and that they were only one method of three used to gather data is considered to compensate for the small number of interviewees. The information acquired with all these methods was considered sufficient for the scope of this thesis.

4.4. Analysis

The research method was designed to be able to answer the 6 sub-questions, and that way the research question. Therefore, the data gathering focused on the importance of electricity in the society, the system´s vulnerability to a large-scale volcanic eruption in Öræfajökull, the operators' planning and organization of emergency management and measures in use.

The theoretical models presented in chapter 3 were used to evaluate the quality of the operators´ emergency management. By comparing the operators´ planning with the emergency management process presented in chapter 3.5.1. it was investigated if and how their planning went through the most important phases according to theory. How well their planning and organization complied with principles presented in chapters 3.5.1. and 3.5.2. also contributed to evaluating the quality of their emergency management. Comparing the operators´ measures with the different types presented in chapter 3.5.3. revealed which types of measures are in use, technical, organizational or operational. The comparison of the results with the theoretical model helped identifying the critical factors as the theory in fact involves suitable organization and principles in emergency management.

Due to little existing research in the field and the relatively small scope of this thesis, the analysis largely consisted of assessments and evaluations based on the authors understanding rather than development of hard facts. The critical factors identified were therefore relatively general but nevertheless important values, guidelines or principles for the operators to have in mind in their emergency management.

4.5. Reliability and validity

In quantitative research, *reliability* refers to the replicability of methods and results. In qualitative research on the other hand, the reliability is related to consistency (Leung, 2015). This thesis used many different data sources and gathered data as needed. It took advantages of unforeseen opportunities along the way and responded to setbacks by finding new ways to reach the goal. When possible, data gathering and analysis were done simultaneously. The researcher´s approach and questions changed somewhat between interviews and even within the interviews, depending on the interaction with the interviewee and the information he or she gave. This was done to get the most out of the interviews, acquire as much information and understanding of the operators´ management as possible. Therefore, the research method could not be entirely predetermined before the information gathering started. However, good sub-questions that were central in the study and an interview guide with predefined topics promoted consistency and that way limited the loss of reliability.

According to Silverman (2009) there are more ways to enhance the reliability of methods and results. Among those are constant data comparison, something that in this thesis is achieved by comparing the data from the interviews with data from the literature and observation. Comprehensive data use is also important (Silverman, 2009), something that is achieved by using both interviews, literature and observation.

In qualitative research, *validity* refers to whether the final product truly depicts what it claims to depict. This can also be described as the "appropriateness" of the tools, processes, and data. This involves speculations about whether the research question will lead to the desired outcome, whether the research methods are appropriate for answering the research question and whether the results are valid for the context (Leung, 2015).

In this thesis, the goal was to identify factors (principles, organizational factors and external influences) that electrical operators should account for in their emergency management for a large-scale eruption in Öræfajökull. That is clearly stated in the research question. In chapter 4.1. it was furthermore explained why the 6 sub-questions are appropriate to help answering the research question and in chapter 4.4. the theoretical models´ importance in the thesis were discussed. The research methods are furthermore considered appropriate for the research topic. They take into consideration that the topic is not widely studied and that there is limited experience with the phenomenon. The decisions to use multiple different data gathering methods and to make use of opportunities along the way increase the probability of good results.

However, a shortcoming involving those different methods is that they are not independent. The flooding and ashfall scenarios in the exercise are based on the only such research available for Öræfajökull, that is literature from Pagneux et al. (2015-a) and ashfall model from Sara Barsotti at the Icelandic Meteorological Office (Barsotti et al. 2018). Those same sources are used in the literature review in this thesis. Finally, the interviewees also to some degree base their assumptions of damage and disruptions on them.

Statistical information is clearly lacking, as there has not been an eruption since 1728. Therefore, it becomes hard to verify the expected damage due to an eruption, the effectiveness of measures, and other factors. Those things are assessed based on general research from other countries and expert assessments acquired in interviews. The experts again base their assessment on experience from eruptions in other Icelandic volcanoes, which are variously applicable. However, it is considered that because the critical factors that the thesis strives to define are relatively general, those assessment do not need to be so accurate.

4.6. The role of the researcher

In this thesis, the author is the main instrument of research. Therefore, the author strived to remain neutral during data gathering and analysis, have an open mind for new information and avoid drawing conclusions based on emotional or practical factors.

Apart from being an inhabitant in Iceland and wanting a reliable electrical system and good public safety, the author had no special involvement in the topic of the thesis. She neither works for the electrical operators nor lives in the area closest to Öræfajökull. Therefore, emotional attachment is minimal. However, somewhat biased opinion might have been developed, both because all the interviewees worked for electrical operators and because of the author´s part in organizing exercise 19-2. The conscious goal to remain neutral, the author´s and interviewees´ common benefits of unbiased evaluation and the constant comparison with literature is hoped to have minimized this.

4.7. Ethical questions

The research topic is not considered particularly ethically sensitive. Even though the sub-questions touch on the vulnerabilities of an import critical infrastructure and its operators´ ability to control them, the main goal of the thesis is to identify factors that lead to good emergency management. This is in everyone´s interest and therefore honesty and uprightness were central in the interviews as well as the exercise. The thesis was done in good cooperation with the electrical operators. Overall, the ethics in this thesis should be good.

5. FINDINGS

This chapter presents the findings gained from literature, from the experience of preparing and monitoring exercise 19-2 and from meetings with interviewees from Landsnet and RARIK. The structure of the chapter is organized around the 6 sub-questions, one sub-chapter for each sub-question.

5.1. Society´s dependency on electricity

Figure 1 in chapter 1.1. gives an indication of how other critical infrastructure are dependent on energy systems. In Iceland, the three main energy systems are fossil fuel that is mostly used in transport, geothermal water that is widely used for heating and electricity that is used for everything else. There is a common understanding that electricity is vital for society, and that nothing really works without it. On top of that, electricity is extremely important when responding to emergencies and evacuating people. Those activities are highly reliant on GSM, TETRA and internet services for communication and information sharing. The interviewee from Landsnet reported that the telecommunication system has around 2-5 hours of backup power, so if the electrical operators have not managed to fix a power outage after that time, additional challenges arise.

RARIK´s interviewees pinpointed that although a large eruption in Öræfajökull would be a huge long-term problem for the society, land and living environment close to the volcano, it would not necessarily be so severe for the company´s role as an electrical distributor. There is only need for a distribution system if there are people in the area. The eruption in 1362 destroyed the area now called Öræfi completely, leaving it deserted for a decade afterwards (Thorarinsson, 1958), and it is likely that an event of similar magnitude would also result in temporary abandonment of the area. Therefore, repairing the electrical distribution system closest to the volcano might not be a pressing matter.

The reparation of the transmission system would however be more urgent. As of today, the transmission line south of Öræfajökull is an important part of the system´s interconnection. That interconnection is important not only for the redundancy in the system but also for the capacity. Landsnet´s interviewee reported that without the so-called Prestbakkalína, that most definitely would get damaged in a jökulhlaup from Öræfajökull, they could unlikely maintain normal service in the east and northeast part of the country.

5.2. Vulnerability of system

In preparation of the exercise and during the interviews it became clear that the electrical system has some vulnerabilities that could lead to problems in case of an eruption in Öræfajökull. Then again, other factors of the system add to its robustness and make it able to withstand demanding conditions.

5.2.1. Jökulhlaup

In preparation for the exercise, Landsnet concluded that a jökulhlaup from Öræfajökull would cause the overhead transmission line called *Prestbakkalína* to break and with it the system´s interconnection. It would unlikely result in power outages but it might lead to reduced capacity in the east and northeast parts of Iceland as the electricity would have to travel a much longer distance with subsequent losses. In such a situation, Landsnet might have to reduce electrical transmission to users with contracts of so-called "unsecure energy". Those are e.g. companies in the fishing industry, greenhouses and other actors that can survive without electricity for some time and Landsnet has special agreements with. At worst, they would have to ration the power, e.g. by giving all users 50% of what they normally need or by giving one area power for a specific period and then another area power for the next period.

Landsnet´s interviewee explained that to prevent these reductions, there is a need for additions to the system, e.g. a high voltage line connecting the two power stations *Fljótsdalsstöð* in the south and *Krafla* in the north. They have however not succeeded in getting these changes through. As for now, users will in this type of event have to endure reduction in service until the system has been repaired.

RARIK´s interviewees expected that any installations in the flood´s path would be washed away. This applies to overhead lines, towers and substations, as well as underground cables. The underground cables are normally between 70-90 cm below the surface but the power of a jökulhlaup is such that this depth would unlikely be enough to withstand it. Because RARIK's system is not interconnected, damage on the cable east of Skaftafell would cause localized power outages. Until it is possible to repair the damage, there are two ways to restore power quickly. One is to use reserve power, e.g. emergency generators, and the other is to disconnect at the so-called switching stations, making a new end on the system and limiting the power outage to an area that should be evacuated anyways. Switching stations are in several places on and near the possible flooding area, in Fagurhólsmýri, Hnappavellir and Reynivellir. They can be remotely controlled through the GSM system. Therefore, the response can be quick even without sending staff into areas with heavy ash or tephra fall. However, as the remote control is dependent on GSM signal it is important that the GSM senders have their own emergency generators.

For situations and areas where the switching stations do not help, reserve power is important. RARIK has a movable emergency power generator south of Öræfajökull, currently located in Freysnes. According to their emergency response plan, the generator is supposed to be moved to Skaftafell in the so-called uncertainty phase of the emergency, when an eruption in Öræfajökull seems to be imminent. Should a jökulhlaup damage the underground cable, the generator can then be used to produce power locally. Skaftafell is outside the supposed flooding area so the generator would be safe there.

According to RARIK´s interviewee, they have been trying to get a permission to move the emergency generator to Skaftafell and permanently keep in there instead of in Freysnes. The problem is that Skaftafell is a popular national park and having a diesel generator located there is not considered attractive. RARIK's informants further told that the company had been discussing if there should be emergency generators on the allocated "safe spots", where people are supposed to evacuate to in case of a sudden eruption and following flood. They concluded that this should be decided together with the Civil Protection Department of the National Commissioner. Discussions about who should be responsible for such generators would have to follow.

5.2.2. Tephra fallout

Tephra fallout could also cause disruptions or at least problems that would require response in order to prevent disruptions. As explained in chapter 2, the main problem with tephra fall for the electrical system is that it tends to stick to insulators on the lines, especially in moist conditions, causing flashover risk. If the load is large enough, it may furthermore cause breakage of lines, towers and other equipment. Therefore, it is important to clean the tephra from installations before it causes problems. In a large eruption the ash can spread hundreds or even thousands of kilometers, and in unfavorable wind directions it might cause problems all over Iceland. Therefore, all electrical operators need to be prepared to deal with ashfall, not only those closest to the volcano. All interviewees talked about the importance of being able to clean the ash from the insulators. For that, equipment and manpower are needed, both that may require cooperation between the companies as well as help from external actors.

In the recent years, the trend in RARIK´s system has been to gradually replace overhead lines with underground cables. When this is written RARIK´s distribution system is 26% monophasic lines, 13% three-phasic lines and 62% underground cables. The company's goal is to have shifted entirely to underground cables by 2035. According to RARIK´s interviewees, this has a major effect on the system´s sensitivity to ashfall as tephra can only accumulate on overhead lines, making them the vulnerable part of the system.

According to the interviewees, no previous eruption that they know of has caused flashover problems in the Icelandic transmission system. Furthermore, the only eruption that has caused problems for the distribution system was the one in Hekla 1980. Then conductive wet ash caused insulator flashover in the county Húnavatnssýsla in North-west Iceland. To make matters worse, the clean-up was difficult, because the wet ash was as glued to the insulators. However, the fact that ashfall has not caused problems in other eruptions, e.g. Eyjafjallajökull 2010 or Bárðarbunga 2015, implies that the system is generally strong and able to withstand a lot of ashfall, at least in favorable weather conditions.

In general, the distribution system is relatively robust when it comes to an eruption in Öræfajökull. There are a few parts of the system that are sensitive to ashfall, mainly the overhead lines. As the system is not interconnected, insulator flashover and damages on the underground cable might cause short-term localized power outages. That can however be mitigated by disconnecting at switching stations and running emergency generators. In addition, the area without electricity due to jökulhlaup will most likely be evacuated during the eruption, resulting in minimum need for electricity.

5.3. Emergency planning

5.3.1. Situation assessment

The interviewees related that an eruption in Öræfajökull is an event that only recently is started to be considered as a threat to the electrical system. Operators are still very uncertain about how large the threat is and what problems it could cause in their system. Their understanding of the eruption is mostly based on predictions of renown scientists, such as the predictions described in chapter 2. The operators´ evaluation of the consequences of an eruption is then largely based on expert assessments, mostly of experts that have worked in the field for decades and experienced eruptions in other volcanoes.

According to the interviewees, these experts, many approaching retirement, have not seen the use for written risk assessments or analysis so they exist to a great extent only in their heads. Therefore, in their documents, the operators have not assessed the threat of an eruption in Öræfajökull and the risks related to it in a particularly detailed or systematic way. Their assessment rather consists of a summary of facts on Öræfajökull and speculations on possible eruption scenarios. For example, RARIK´s emergency plans all start with an introduction that serves as a kind of risk assessment or risk analysis, discussing possible and probable effects that the event could have on the system.

5.3.2. Mitigation

The operators have various methods for mitigation. Some of them are mentioned in chapter 5.2. in context with the vulnerabilities. All four mitigation strategies presented in chapter 3.5.1. are used to some extent. To recap, the strategies are avoidance, acceptance, transference and reduction. For example, replacing overhead lines with underground cables is a way of avoiding flashover risk. That does however not eliminate the possibility that the cable is swept away by jökulhlaup. That risk is simply accepted, because it is limited to a relatively small area and it is hard to control. The contracts of “unsecure power” are a way of transferring the risk. Operators sell users with such agreements cheaper electricity traded with being able to cut their power in case of shortage, without being held accountable. Finally, various measures are used for reduction. An example is the installing of emergency power generators to prevent or shorten the period of power outage should there be disruption.

The measures will be presented more systematically in chapter 5.5.

5.3.3. Preparedness

To enable an effective response in case of an emergency, the operators have developed emergency response plans, variously detailed. According to the interviewees, the companies have very experienced staff who has worked in the field for decades, and their competence is considered to reduce the need for detailed emergency response plans. However, this type of thinking is changing, as the experts are getting closer to retirement age and new people are taking over.

The plans that Landsnet currently use are basically only short general checklists with the main actions required in case of an emergency. They do not necessarily apply to specific events, but rather to eruptions, storms or other general events. E.g. the plan provided in the interview applies to eruptions and is a A4 sheet with a very rough to-do list for actions in different phases of the event. The phases are investigation phase, uncertainty phase, alert phase and emergency phase. Currently, Landsnet is working on extracting knowledge from experienced employees and writing more detailed emergency response plans for specific lines or substations. Those plans include information on the equipment in the substations, accessible resources, experienced operators etc. Landsnet has identified the most critical parts of the system and is prioritizing detailed plans for those.

RARIK already has more detailed emergency response plans for the event of interest. For a volcanic eruption in Öræfajökull, RARIK has two relevant emergency response plans. One is general for an eruption in Öræfajökull and the other is specific for ashfall.

The plan for an eruption in Öræfajökull was initially published in January 2018 and is currently (March 2019) being updated. According to the plan, its goal is to make RARIK´s response quick and well organized should there be an eruption in Öræfajökull. The plan covers the company's actions and operation leading up to an eruption, during the eruption and directly after it. It includes an action list for the four different stages of the emergency: uncertainty phase, alert phase, emergency phase and post-emergency. In the plan´s ANNEX, the action list is written as a checklist. The actions involve preparing and using e.g. emergency power generators, filters to protect equipment from damage and ash cleaning equipment. It also instructs when to contact other actors such as Landsnet who they might want to share staff and equipment with, farmers and contractors in the area that could possibly help with clean-up and petroleum companies to ensure enough fuel for the emergency power generators.

This response plan applies only to the areas closest to the volcano, that is for the south and east sectors of RARIK´s system. Ashfall from the eruption might however cause trouble anywhere in the country, depending on its magnitude, characteristics and wind direction.

Therefore, a separate emergency response plan for ashfall has been developed. That one is to be used all over Iceland, regardless of the location of the volcano.

The response plan for ashfall describes the possible impact of ashfall on RARIK´s distribution system and operations, as well as instructing appropriate emergency response. The action list in this plan is broken up in the same phases as the response plan for an eruption in Öræfajökull, that is uncertainty phase, alert phase, emergency phase and post-emergency. It includes many of the same components but with larger emphasize on the staff´s personal health and safety as well as monitoring weather and ashfall forecast. There are also descriptions of how to clean ash from equipment.

According to the interviewees, RARIK´s goal is to review their emergency response plans once a year. Exercises, such as the one in February, provide a golden opportunity to review and test out response plans and subsequently update them if necessary. Landsnet´s interviewee related that as their current emergency plans are short and general, they are considered almost timeless. This will however change when they take the detailed plans that they are working on now in use.

RARIK´s interviewees believe that should there be need for reparations of the system, they will be well equipped to respond. They normally have some extra cable and spare parts stored, and they also have good relationship with the companies Rönning and Orkubú Vestfjarða that can sell or lend them cable on short notice. On top of that, RARIK´s interviewees believe that they will have time to plan the reparation work, as an eruption in Öræfajökull is likely to last for days or weeks. Landnet´s interviewee had a similar story to tell. To prepare for a quick recovery from jökulhlaups, Landsnet has used the flooding models from the Icelandic Meteorological Office to analyze how many meters of line, how many towers, insulators and other equipment could be damaged in the worst-case flooding scenario. Now they are making sure they have enough spare parts for this worst case, placing them in convenient locations and buying what they do not have already.

5.3.4. Exercise 19-2 as a performance assessment

As there has not been an eruption in Öræfajökull since Iceland was electrified, the performance of the operators´ emergency management must be assessed subjectively and by try to imitate real events in exercises. Excersice 19-2 served for example as a kind of performance assessment for the participants´ emergency response. It dealt with a 1362-like eruption in Öræfajökull with a following jökulhlaup and heavy ashfall. In the weeks before the exercise, participants were informed that the volcano was showing signs of unrest, and that an eruption might be imminent. That gave them time to go over their plans and make proper "arrangements" with equipment, spare parts, manpower and other resources. On the exercise day, Öræfajökull started "erupting" early in the morning, so participants had to mobilize their emergency organization, act according to their emergency plans and respond to "problems" and "disruptions" that came up. Damages, disruptions and actions were imaginary but the communication within companies and between actors was real. Through TETRA radio, Workplace, e-mail and phone they acquired and shared information and coordinated their actions. The imaginary epidemic outbreak added an extra dimension, as some of the participants did not even manage to maintain normal operation, let alone respond efficiently to a big emergency.

As much as can be concluded from the electrical operators´ simulated actions, it seemed that they were well equipped to respond to a large-scale eruption in Öræfajökull. RARIK was quick to restore electrical service after temporary localized outages and all the operators immediately started to plan ahead and prepare for possible problems in the hours or days to come. The exercise gave an even better indication of the participants´ communication, information sharing and decision making, as those activities were tested in reality. For the electrical operators, it revealed the need to coordinate procedures for authority and TETRA communication between companies.

In exercise 19-2, TETRA radio talk groups were merged with the thought of making information sharing and coordination more efficient. However, it also led to extreme traffic on the channel, and a lot of information sharing that should rather have been internal in special companies. Participants were unhappy about that in the beginning, reparation groups were using this talk group to communicate internally and with their control centers. According to participants, problems with telecommunication come up in almost every exercise.

The exercise also displayed the potential benefits of a common action logging database. Those factors will be further discussed in chapter 5.4.

5.4. Organizational factors

5.4.1. Operation and authority

According to the interviewees, the organization of the companies´ operation and authority contributes a great deal to their performance and ability to prevent and respond to problems. Landsnet's interviewee described how the company has three levels of operation, normal, disruption and emergency operation.

Professionalism and good procedures have proven to be an effective way to prevent failure and disruptions, and therefore everything is thoroughly planned during normal operation. Landsnet´s interviewee explained that a week before any project is started, no matter if it concerns grid control, maintenance or construction, all working documents need to be ready. Those are design and technical documents, risk assessments, spare part lists, list of employees working on the project etc. Because of this, there are fewer mistakes and employees have time to prepare for upcoming tasks. The only time this rule is broken is in case of a sudden unexpected disruption or failure. Landsnet´s interviewee said that after this practice was implemented, disruptions had noticeably gone down. The practice allows for a better monitoring of the system, better organization of projects and more disciplined work procedures. During this type of operation, the actual job is mostly done by operators in the field while the management of the grid is in the hands of the control center in Reykjavik.

Disruption operation then involves an unexpected sudden event, failure in the system or hazardous outer conditions, such as a storm, vandalism or threats. To responding to such a situation, a special standby team of experienced staff is activated, who assist the control center with management and decision making. The first thing they do is to assess the situation, how severe the disruption is and what effects it will have on the transmission system. They then summon people to take care of the situation, fix the failure, clean ash, ice or salt from lines and so on.

If the disruption is large enough, the operation goes to emergency phase. Disruptions are normally categories in green, yellow, orange, red and black. Response to the first three categories can be handled within disruption operation while the latter two require more extensive actions. Here we are talking about disruptions that affect many users and take more than 5-8 hours to fix. In an emergency phase, the emergency management team (EMT) is activated to help the control center and the standby team. Members of the EMT are the company's CEO, safety manager, heads of departments and experienced staff. The EMT has the final word in case of critical decision making. It also acts as the contact to users´ EMTs and the authorities for dissemination of information about the situation.

RARIK's management of emergency response for the electrical distribution works differently. The system has four separate sectors, north, south, east and west. Each of these sectors has a site manager and in normal conditions, the sectors operate mostly independently. In severe situations, the company's emergency management team (EMT) is activated. The team takes control of coordination, decision making, prioritizing of tasks, communication with external actors and more. By suddenly transferring the normal authority and tasks of the site four managers to the EMT they switch out the normally decentralized management form for centralized management.

Landsnet and many other actors however prefer conducting "business as usual", that is keeping their organization in emergencies as close to normal as possible. This has created some confusion, since communication channels change, as actors from Landsnet and other companies that are used to directly contact RARIK´s site managers about e.g. borrowing equipment and manpower are suddenly not allowed to do that anymore.

RARIK´s interviewees believe that a top-down management with a dominant EMT is beneficial for their emergency management. They believe that it promotes good overview, correct priorities and coordinated efforts. The team works closely together with the four site managers as well as the EMT´s of other companies and institutions. However, they say that there is a fine balance between a too centralized management and a too decentralized management. During a large event it will most likely take a few hours or days to find the perfect balance.

5.4.2. Cooperation

In the interviews, all the interviewees focused on the importance of good relationships and cooperation between actors. RARIK´s interviewees mentioned that the different companies have a common responsibility to maintain service to as many users as possible. Therefore, the company would rather send their staff and equipment to help fix a large problem in Landsnet´s system, than to fix a small problem in their own system. The interviewees stated that there is a longstanding tradition of cooperation in the electric sector in Iceland, in heavy failures and emergencies as well as small problems. This has not been impaired by the recent law on competition in the electric market. An example of this is that in wintertime ice tends to accumulate on overhead lines, increasing the probability of breakage. The removal of this ice is often done by the electrical staff that is closest to the site, regardless of which company they work for and which company owns the lines.

Samorka (the association of the Icelandic electricity industry, district heating, waterworks and sewage utilities in Iceland) has contributed to this cooperation along with the consultative forum NSR. Of these two phenomena, NSR is more focused on emergencies and severe events. It has served as a catalyst for emergency preparedness and response as well as a platform for acquaintances between the members, since actors cooperate better when they already know each other. NSR also disseminates information on who has special knowledge, equipment or spare parts and where to seek extra assistance.

NordBER is then a similar phenomenon, a contingency planning and crisis management forum for the five Nordic countries, Iceland, Norway, Sweden, Finland and Denmark. Participants also meet regularly, share their knowledge and experience and help each other out in times of need. They regularly have common emergency exercises, e.g. one on cyber security in autumn 2018. Landsnet´s interviewee told that this cooperation had proven very useful a few years ago when the submarine cable to the Westman Island failed. Through NordBER they soon got a cable ship with specialists that could fix the problem faster and better than would have been possible with local resources.

5.4.3. Information sharing

Findings revealed that good information sharing between actors is the key to effective cooperation, during normal operation and emergencies alike. It stimulates coordination by making sure that actors are familiar with each other´s resources and procedures and helps operators learn from each other´s experiences. During normal operation, meetings and conferences organized by NSR or Samorka provide opportunities for information sharing. The same applies to professional groups, rapports and any other forums where important topics in the electrical sector are discussed. In emergencies, operators have been using phones, e-mail and TETRA radio for communication and information sharing and in some cases some form of a common action register. Public and social media is then important to disseminate information to the public.

TETRA radio is a common telecommunication tool for response actors as well as electrical technicians and reparation groups out in the field. The TETRA system is generally more reliable that the GSM network, providing reception in more places. It has the possibility of communication through talk groups, were everyone in the group can listen and speak between them. Also, it is possible to use a TETRA radio as a normal phone, calling another device by dialing its number. Finally, it can be used as a GPS and a tracker, that way giving the operators´ control center an overview of their employees´ location.

An alternative option for information sharing and coordination is a common event and action register where actors log what is happening and what is being done. It is a way to keep everyone updated without constant phone calls or radio communication. Participants in exercise 19-2 mentioned that it is much easier to extract key information from a written register than from oral communication. In emergencies when a lot is going on, one person can monitor the register and highlight important messages. In such situations, it is on the other hand difficult for one person to keep track of radio messages. An option for such a common register is the database SAReye, which originally was designed for the Icelandic Search and Rescue Teams (ICE-SAR). It is currently used by Landsvirkjun, Landsnet, the National Commissioner´s Department of Civil Protection and Emergency Management and ICE-SAR. Most of these parties use the database in all projects, big and small, both in normal operations and emergencies. It would be beneficial if other members of NSR would also take SAReye in use, and in times of emergencies share their internal action register with other response actors.

In real events, the media, both the press and the social media, plays an important role in disseminating information to the public. It is an important task of the public relations (PR) staff of the immediate actors to give information to the media that is informative and helpful in the given situation. Many parties will have to establish a media team in real events like the National Commissioner´s Department of Civil Protection and Emergency Management did during the eruption of the Eyjafjallajökull in 2010. Other parties will assign the job to their PR staff with support of the EMT. In exercises, this part of the response is trained in different dimensions. For each exercise the suitable form is chosen, e.g. written e-mails, online media reports or communication with journalists.

5.5. Measures

It is clear that in the event of a large-scale eruption in Öræfajökull, the electrical system would be exposed to both jökulhlaup and tephra fall. There are mainly three types of problems that this might cause, 1) that installations are washed away by jökulhlaup, 2) insulator flashover and 3) breakage of installations due to heavy tephra load. If problems occur, the operators will respond by first trying to minimize the disturbance and then later on restore normal operation, e.g. by repairing the damage.

Measures to control the risk are an important part of the operators´ emergency management. Operators have planned for proactive measures to mitigate the risk before a problem occurs and reactive measures to reduce the scope or duration of the problem after it has occurred. This thesis has identified some of these measure and presented them in chapter 5.2. in context with the system´s vulnerability or robustness.

Figure 13 explains the measures in a graphic way along with possible factors influencing the development of problems and possible ways to respond to them. The figure is based on findings from all sources, interviews, exercise 19-2 and literature. Central in the figure is a red starshape representing a problem. On its left side there are factors that could cause problems and factors that influence them. A gray arrow pointing from one box to another represents that the first factor influences the second. The colored boxes stand for the different types of measures, yellow for technical measures, blue for organizational measures and green for operational measures. On the right side of the problem there are possible ways to respond to them. The black arrows indicate that when there is a problem, the operators must first try to minimize the disturbance and then restore normal operation by repairing the system. The yellow arrows represent different ways to minimize disturbance, that is alternate power or to reduce demand. Then again, there are different ways to do that. As before the grey arrows represent that one factor influences another and the colored boxes are different types of measures.

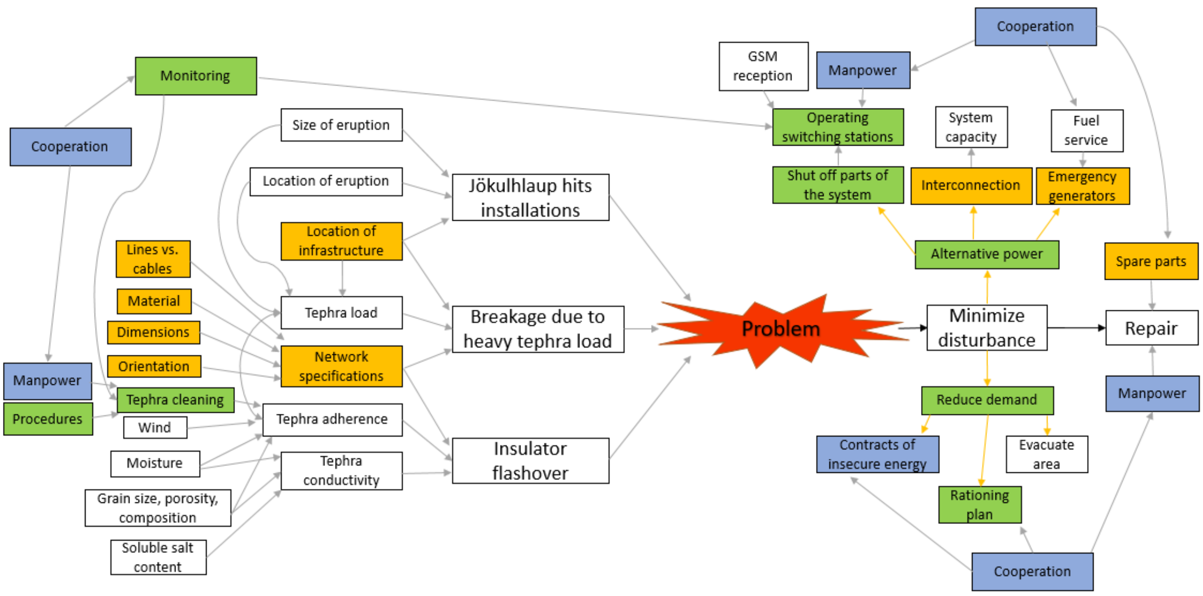

Figure 13: Causes for problems (disruptions or damage) in the electrical system due to an eruption in Öræfajökull and measures to control the problems.

Figure 13 is not considered to illustrate a complete model. Its goal is to give an idea about how the operators´ measures can affect the scenario and graphically show how different factors are connected. It is based on the author´s understanding of the situation and it is likely that experts with better knowledge and understanding of the system would suggest some alterations.

5.6. Possible improvements

Various improvement potentials in the operators´ emergency management were found in the planning and organization. Those will be discussed in chapter 6. The thesis has also identified that the emergency management for an eruption in Öræfajökull is based on too limited knowledge. It is largely based on expert assessments and experience from variously applicable former events. Therefore, there is urgent need for more research in the field.

6. ANALYSIS

This chapter discusses the results presented in chapter 5 and defines critical factors that electrical operators should account for in their emergency management based on them. In addition, there is a special sub-chapter on uncertainties in the thesis.

6.1. Society´s dependency on electricity

Even though many important functions in society, e.g. the telecommunication system and hospitals, have their own emergency generators, they are only designed to cover the need for a few hours. It is evident that long-term disruptions in electrical service would have a negative impact on emergency response in case of a volcanic eruption in Öræfajökull and on the function of society afterwards, both in the area closest to the volcano and possibly all of Iceland. Therefore, it truly is of value to search for the critical factors whereas good emergency management can reduce the probability and severity of disruption in case of an eruption.

As explained in chapter 5.1., electricity is vital for the functioning of modern society. In an evacuated area, as might be the case in the area Öræfi after an eruption, there is less need for electricity. Therefore, restoring the electrical distribution in Öræfi after an eruption might not be very urgent. On top of that, RARIK has emergency generators that are expected to take care of the need during evacuation and response. The transmission lines south of Vatnajökull are on the other hand an important part of the interconnected transmission system of the country and a failure there could affect the capacity of a much larger area. Therefore, the first critical factor identified is that *after a large-scale eruption in Öræfajökull reparation of the transmission system in the area Öræfi is more urgent than the reparation of the distribution system*. How the operators choose to deal with this fact is the subject of further investigation. As the distribution all over Iceland is dependent on the transmission system, it may in some cases be applicable to both the transmitters and distributers to work together to quickly repair damages in the transmission system.

6.2. Vulnerability of system

The main volcanic hazards due to an eruption in Öræfajökull that could cause problems for the electrical system are jökulhlaups and tephra fallout. Jökulhlaups would destroy everything in its path, but the good thing about them is that they are very local hazards. Flooding models therefore give a good indication about which part of the electrical system is in danger. A critical factor identified on this basis is that *electrical operators should prepare for the damage of all installations on estimated flooding areas and arrange a response to the damage*. RARIK is doing this by having good agreements and cooperation with suppliers and Landsnet is doing this by analyzing what parts of the system might get damaged and assembling spare parts. This is all good, but the fact that a jökulhlaup from Öræfajökull would break Landsnet´s interconnection and likely cause reduction in service in the east and north-east parts of Iceland is still a problem. Therefore, another critical factor is identified: *Additions to Landsnet´s system that increase its reliability and capacity are urgent.*

There is more uncertainty involved with the tephra fallout, that mostly can cause two types of problems, insulator flashover and breakage of lines and towers because of heavy load. Weather factors and characteristics of the tephra largely control the spreading, accumulation, weight and conductivity of tephra on structures, making it necessary to account for different conditions when assessing the risk. This leads to identification of another critical factor: *The operators´ emergency management must account for the uncertainty about the external factors that influence tephra induced risks*. Here, tephra induced risks refer to flashover risk and risk of breakage because of tephra load and the external factors are e.g. weather factors such as wind and humidity and characteristics of the tephra such as grain size, composition and soluble salt content. As the tephra may in inconvenient conditions spread all over Iceland another critical factor is that *operators all over Iceland must prepare for the possibility of problems due to tephra fallout*.

6.3. Emergency planning

Although the operators´ tools for emergency planning are not very detailed or systematic and still in development, they have in their work gone through all the planning phases presented in chapter 3.5.1. Table 2 summarizes how they fulfil the objectives of each phase, situation assessment, mitigation and preparedness.

Table 2: The operators´ compliance with the planning phases presented in chapter 3.5.1.

Planning phase	Landsnet	RARIK
Situation assessment	Expert assessment: Summarize information about Öræfajökull, speculate on possible eruption scenarios and their effects on the electrical system.	
Mitigation	Various measures to avoid, accept, transfer or reduce risks. Some measures were implemented especially to deal with risks found in the situation assessment while others were already in place.	
Preparedness	Short and general emergency response plans although more detailed plans are in creation. Identification of useful and available resources and investment in spare parts. Regular exercises.	Emergency response plans on 1) an eruption in Öræfajökull and 2) ashfall that are updated regularily. Identification of useful and available resources. Regular exercises.

As summarized in table 2, the electrical operators´ emergency planning and preparedness relies heavily on their employees´ qualification and expertise. Instead of formal risk and vulnerability analysis, the situation assessment is based on expert assessment and is in some cases not even written down. On top of that, the short and general emergency response plans give the employees responding to problems a lot of added responsibilities and many opportunities to overlook important factors and make mistakes. However, this is not all bad. The emergency management guideline presented in chapter 3.5.1. is the importance of flexibility, that is the importance of organizing the emergency management in such a way that there is room for improvisation and adaptation to new conditions. There is a fine balance between too formal risk management and too flexible and it seems like the electrical operators are still working on finding that balance. This leads to identification of a critical factor: *Operators must find a balance between formal and flexible risk management that reduces the probability of human error while also leaving room for improvisation*.

The operators´ performance in the executional phases of the emergency management, response and recovery, cannot be fully evaluated at this time as it has not yet been tested during an actual eruption in Öræfajökull. It has however been tested in relation to eruptions in other volcanoes, when the response and recovery seem to have been successful. The response has also been tested in exercises, such as exercise 19-2. The operators furthermore claim to be positive that when Öræfajökull erupts, they will be well equipped to handle the situation.

The interviewees though admit that there are many uncertainties involved. They do not know for certain how a large-scale eruption in Öræfajökull would affect their system and how easy it would be to manage the situation. This leads to speculations about whether the operators are accepting more risk than they realize. Are they perhaps overconfident with their system and their ability to respond, simply because they have never experienced disasters of the magnitude that a large-scale eruption in Öræfajökull might turn into? Do the experts assessing the risk consider the hazard smaller and the system more robust than it is, just because previous eruptions in other volcanoes have not damaged the system? These speculations lead to identification of a critical factor: *Operators must recognize the possibility of a larger eruption than modern society has ever experienced and prepare for the worst-case scenario.*

It is furthermore suggested that this worst-case scenario that the operators should prepare for is a 1362-like eruption. In chapter 3.3. it is argued that a 1362-like eruption in Öræfajökull can be viewed as the worst-case scenario that still is plausible. It represents a low probability but high consequence event, a possibility that is remote but real. In the believe that electrical operators, and in fact all the Icelandic response system, should hope for the best and prepare for the worst a critical factor is identified: *A 1362-like eruption in Öræfajökull should be identified as a low probability but high consequence design event for Iceland´s national emergency management, as well as the electrical operators´ emergency management.*

6.4. Organization

Organizational factors clearly play an important part in the operators´ emergency management. As Landsnet´s interviewee related, good work procedures have helped reducing failure and disruptions during normal operation and helped summoning the right people to respond to problems and emergencies. However, the fact that the different companies do not use the same authority organization in their emergency management has complicated their cooperation. To explain this more systematically, table 3 summarizes how the actors comply differently with the four fundamental principles presented in chapter 3.5.2.

Table 3*: The operators´ compliance with the four central principles presented in chapter 3.5.2.*

Principle	**Landsnet**	**RARIK**
Responsibility: The actor that normally is responsible for a specific task or sector in society is also responsible for emergency preparation and response in that sector.	Both companies comply with this principle. They are aware that they are responsible for the emergency management in their own system and are actively doing their part in the preparation.	
Equivalency: The organization or structure established in emergencies should be as similar as possible to the organization normally operated with.	The comply well with this principle by striving to maintain “business as usual”.	In case of emergency, many of the site managers´ tasks are moved to the EMT. This has created confusion regarding authority and communication with external actors.
Subsidiarity: The emergency should be managed at the lowest possible level, e.g. by the affected company if possible or local government.	They comply well with this principle by having the three levels of operation, normal operation, disruption operation and emergency where more people and resources are summoned as needed.	In emergencies, RARIK uses a top-down management with their EMT at the top.
Cooperation: All actors have an independent responsibility to coordinate their preparation, response and emergency management with other relevant actors.	Both operators comply with this principle. They claim to have good agreements and relationships with relevant actors and actively take part in the NSR cooperation and exercises.	

Table 3 highlights that Landsnet complies well with the four fundamental principles while RARIK only complies well with two of them. They deviate from the principles of equivalency and subsidiarity by moving the site managers´ normal tasks and responsibilities to the EMT during demanding situations. It may be that this really is the best organization for their operation and that it in fact promotes better overview, prioritizing and coordination than if the EMT had less authority. However, the four fundamental principles are widely accepted for a reason. They have repeatedly proven useful and actors have found ways to comply with them but still have an effective EMT to ensure coordination. For example, it seems that Landsnet has succeeded with this. Based on the four principles´ general utility, the author considers it likely that if RARIK would slightly alter their organization to better comply with them, they would not only reduce confusion in cooperation with external actors but also achieve a more effective management internally. At least is would be beneficial if there was consensus in the electrical sector about how the authority organization in emergencies should be. On that note a critical factor is identified: *Operators should agree on one form of emergency organization with respect to authority. Ideally, they should strive to comply with the four fundamental principles about responsibility, subsidiarity, equivalency and cooperation.*

Furthermore, the results as well as well as theory presented in chapter 3.5.2. emphasize the importance of good cooperation between electrical operators, their clients and official actors. In general, this seems to be in place. Electrical operators recognize their common responsibilities to users and therefore have a long tradition of helping each other out by sharing staff, equipment and other resources. On top of that, NSR provides a structured platform for further knowledge sharing and common exercises. Even though this is all in place, exercise 19-2 underlined recurring problems with telecommunication and information sharing during emergencies. Perhaps this is something that can never be fully avoided. Perhaps emergencies will always be accompanied by some degree of chaos. However, it is clear that better tools and procedures for communication and information sharing enhance the operators´ cooperation and coordination, especially during the first hours of an emergency. The same should apply to other aspects of the cooperation, there is always room for improvements. This leads to identification of a critical factor: *Good cooperation can always be* *improved.* As for now, the first tasks suggested for that are 1) to establish a common event and action register for electrical operators, e.g. by using the SAReye database and 2) to look into procedures for TETRA radio communication in emergencies.

6.5. Measures

Question 5 highlights the proactive and reactive measures that the operators use in their emergency management. The answer of this question compared to the vulnerabilities or robustness identified by question 2 revealed what measures are most important and what could be beneficial to add.

Figure 13 in chapter 5.5. depicted the author´s understanding of the operators´ main measures in their emergency management for an eruption in Öræfajökull. It shows that while the operators have various proactive measures to affect the tephra induced problems, they are utterly helpless against jökulhlaups. Their only mitigation measure for that is smart location of infrastructure. Furthermore, the operators may even be powerless there as the system must primarily be developed with regard to the users´ needs and location, not with regard to possible flooding scenarios. When it comes to reactive measures, the operators also have various ways to reduce or shorten the emergency. However, there are always some external factors involved that they cannot control. E.g. the emergency generators are in the long run dependent on the petroleum companies and switching stations can only be operated if the GSM system is up and running. This leads to identification of a critical factor: *Good emergency management can reduce the risk related to an eruption in Öræfajökull but not eliminate it*.

6.6. Possible improvements

After conducting the thesis, the following improvement potentials for the operators´ emergency management for an eruption in Öræfajökull were defined:

1. The planning process should be more systematic. As for now, the operators have relatively informal tools and procedures for assessing and analyzing hazards, risks and vulnerabilities, applying measures to control them and developing emergency response plans. Even though their trust in their experts´ knowledge and assessments may be well founded, a more systematic way of evaluation, mitigation and

preparedness is considered beneficial. Currently, the operators seem to be changing their ways towards this direction, e.g. by making detailed emergency response plans.

2. A 1362-like eruption is recommended as a low probability but high consequence design event for the emergency management. That would promote that the operators consider the full severity of the hazard and prepare for the worst-case scenario.
3. There is need for better tools and procedures for communication and information sharing during emergencies. The database SAReye may be a convenient medium for a common event and action register. How TETRA radio communication during emergencies should be organized still needs to be determined.
4. The operators should agree on one form of emergency organization with respect to authority. Ideally, they should strive to comply with the four fundamental principles about responsibility, subsidiarity, equivalency and cooperation.
5. There is need for more research in the field: on the volcanic behavior of Öræfajökull, the possible and probable impact that the eruption would have on the electrical system and the society in general, and on the performance of the operators´ emergency management. On that note, the last critical factor is defined: *In order to be realistic, the operators´ emergency management must be based on a solid knowledge base.*

6.7. Uncertainty in the thesis

As discussed in chapter 3.1. there is a lot on uncertainty involved with the preparedness for an eruption in Öræfajökull. Moreover, the assumptions drawn in this thesis and the critical factors identified are based on an incomplete knowledge base with a lot of uncertainty. Here below, the uncertainty will be discussed along with how it affects the results.

<u>Uncertainty about the past</u>: How exactly were the eruptions in 1362 and 1728, e.g. the characteristics, magnitude, impact? How were the following jökulhlaup and tephra fallout? Assumptions about this are based on written sources from shortly after the eruption and researches done hundreds of years later. There is epidemic uncertainty about how correct those assumptions are and aleatory uncertainty about to what degree these former eruptions represent a future event. This contributes to the model uncertainty as the input data in flooding and ashfall models is based on assumptions of parameters from previous eruptions.

Uncertainty in the present: It has already been discussed that the knowledge base for the volcanic behavior of Öræfajökull, the expected impact on the electrical system and the performance of the operators´ emergency management is too limited. There is a lot of epistemic uncertainty involved that could be reduced with more research. More knowledge would give the operators a better foundation for their situation assessment and for their decision making related to mitigation measures and emergency preparedness. That way, it would enhance the operators´ emergency management. However, the epistemic uncertainty is not considered to affect the quality of this thesis. The goal of the thesis and the research methods account for the limited knowledge. Therefore, the critical factors identified are relatively general, and some of them even touch on the uncertainties related to a future eruption.

Uncertainty about the future: There will always be uncertainty about a future eruption in Öræfajökull, its impact on the electrical system and the operators´ capability to manage the situation. The volcanic behavior can be studied and roughly described but still it will never be possible to predict the exact timing, magnitude and characteristics of a future eruption and the following jökulhlaup and tephra fallout. On top of that, weather conditions play an important part in the tephra´s spreading and damage potential and there is always some uncertainty related to the weather, especially far into the future. Finally, people are unpredictable. No matter how good plans and procedures are, there is no way to know exactly how people will behave or respond to a future emergency. This applies also to electrical employees.

7. CONCLUSION

7.1. The critical factors

The goal of the thesis was to identify critical factors, that is principles, organizational factors and external influences, that the electrical operators should account for in their emergency management for a “large-scale eruption” in Öræfajökull. With the help of 6 sub-questions, the operators´ current form of emergency management and its importance for society was assessed. The quality of the emergency management was then analyzed by comparing it to widely accepted theoretical models and important characteristics were discussed. 12 critical factors were defined as they came up in the discussion. Most of the factors are general and some of them apply to the emergency management for any catastrophic event affecting the electric system. They can be sorted into planning factors, organizational factors, factors related to uncertainties surrounding the event and system specific factors:

Planning factors

- A 1362-like eruption in Öræfajökull should be identified as a low probability but high consequence design event for Iceland´s national emergency management, as well as the electrical operators´ emergency management.
- In order to be realistic, the operators´ emergency management must be based on a solid knowledge base.

Organizational factors

- Operators must find a balance between formal and flexible risk management that reduces the probability of human error while also leaving room for improvisation.
- Operators should agree on one form of emergency organization with respect to authority. Ideally, they should strive to comply with the four fundamental principles about responsibility, subsidiarity, equivalency and cooperation.
- Good cooperation can always be improved.

Factors related to uncertainties surrounding the event

- Electrical operators should prepare for the damage of all installations on estimated flooding areas and arrange a response to the damage.

- The operators´ emergency management must account for the uncertainty about the external factors that influence tephra induced risk.
- Operators all over Iceland must prepare for the possibility of problems due to tephra fallout.
- Operators must recognize the possibility of a larger eruption than modern society has ever experienced and prepare for the worst-case scenario.
- Good emergency management can reduce the risk related to an eruption in Öræfajökull but not eliminate it.

System specific factors:

- After a large-scale eruption in Öræfajökull reparation of the transmission system in the area Öræfi is more urgent than the reparation of the distribution system.
- Additions to Landsnet´s system that increase its reliability and capacity are urgent.

Once again, it should be emphasized that the critical factors do not provide an exhaustive list or detailed guidelines on how the electrical operators should handle their emergency management. They are however viewed as important values, recommendations or principles for the operators to have in mind.

7.2. Future work

Further research in this field is recommended, e.g. to investigate better the volcanic behavior of Öræfajökull and the possible and probable impact that an eruption would have on the electrical system. A comprehensive Bayesian network that links possible causes and consequences for problems could be a beneficial analysis tool. Such an analysis would have to account for the large uncertainties regarding the scenario.

It could also be beneficial to construct a tool or scale to measure the performance of the electrical operators´ emergency management. Such a tool should be applicable for the emergency management for any unwanted event and could e.g. include factors such as situation understanding, mitigation, preparedness, capacity, response time and cooperation. Such a performance assessment tool is suggested as a part of the operators´ quality management system.

Finally, it could be beneficial to categorize the Icelandic volcanos in terms of what type of tephra they normally emit, that is composition, grain size and other characteristics. This could give an indication of the flashover risk associated with eruptions in each volcano.

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APPENDIX 1

Interview guide for meeting with interviewees from RARIK (translated from Icelandic):

Introduction: Shortly explain what the thesis is about.

Who are you?

1. What position do you have at work and for how long how you had it?
2. What are your main tasks at work?

Your system

3. Can you explain shortly how your system is built up?
   a. Especially in Öræfum
4. Are some parts of the system especially vulnerable for damage or disruptions due to an eruption in Öræfajökull?
   a. Where and why?
   b. What consequences would damage in these parts have?
   c. What measures have you to control the risk?
   d. What reserve power is available?
5. What other functions in society are dependent on electricity from you?
   a. What consequences has short-term power outage?
   b. How about long-term power outage?
6. What are your responsibilities towards the users?
   a. Regarding security of supply?
   b. Regarding emergency preparedness and response?
   c. Are those legal responsibilities or the company´s own policy?

Emergency preparedness and management - Öræfajökull

7. Can you shortly describe the organization of the company´s emergency management?
    a. What are the most important tasks?
    b. Authority and decision making (centralized or decentralized?)
8. How much have you considered the event “a volcanic eruption in Öræfajökull”?
    a. Do you have a special risk analysis for that event? What about an emergency response plan? Could I take a look at them?
9. What actors within the company are involved in the emergency management?
10. What external actors are involved in the emergency management and how (cooperation, information, …)?
    a. Specifically for an eruption in Öræfajökull.
11. Can you tell me about the NSR forum? What part does that play in the emergency management?
12. Do you use the SÁBF system (control – planning – resources – execution)? How?

<u>Former eruptions</u>

13. Can you tell me about the experience in recent eruptions (e.g. Eyjafjallajökull, Bárðarbunga)?
14. Did the eruptions affect the electrical system? How?
15. Were emergency response plans activated? How useful were they?
16. Did the eruptions reveal any strength of weaknesses? In the system, organization or the management?

<u>Exercises</u>

17. How satisfied are you with exercises that you have participated in, e.g. the ones that NSR organizes? Have they promoted improvements in the emergency management?
18. In the exercise in February, the theme was an eruption in Öræfajökull of similar magnitude as the one in 1362. Did you find out how much such an eruption would affect your system and service?

a. What would get damaged?

b. Where and for how long would there be power outages?

c. How did it go to “respond” to this? Where emergency response plans sufficient?

19. In case of damage, what procedures do you have for restoring and rebuilding??

Something else that you consider important or interesting in this context?

Could I take a look at written documents that apply to an eruption in Öræfajökull?

Interview guide for meeting with the interviewee from Landsnet

The same interview guide as for RARIK. Only there was an extra question:

20. What methods do you use for action logging?