ISSN 2004-2965 Energy Proceedings, Vol. 18, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, in Bangkok, Thailand
Paper ID: 0006

The Swedish Power System Resilience against Bad Weather Conditions

Hou N[1], Duvnjak Žarković S[1*], Hilber P[1], Shayesteh E[2]

1 KTH Royal Institute of Technology, Stockholm, Sweden

2 Swedish National Grid, Stockholm, Sweden

ABSTRACT

As a result of global warming, the frequency of bad weather events has increased raptly, but so has the demand for more reliable power supply. This study investigates the Swedish power distribution system's resilience towards certain weather conditions such as wind, lightning, rain etc. The input data is all unplanned disturbances gathered from the Swedish energy companies (Energiföretagen Sverige) between 2015 and 2019. After sorting and analyzing the data, the results are then compared to the weather data from SMHI (Swedish Meteorological and Hydrological Institute). The results show that on average 21% of unplanned outages are related to weather conditions in Sweden. Of the weather phenomena studied, wind and lightning are significantly affecting the resilience of the power system. One way to prevent outages, especially in lower voltage distribution systems, where most disturbances occur, is to improve the maintenance of the system.

Keywords: climate change, power system, outages, reliability, resilience, weather

1. INTRODUCTION

Over the past century, an increase in greenhouse gases emission has caused the global temperature to rise, leading to climate change. One of the most visible consequences of climate change is the increase in frequency of extreme weather events. Heavier snowfall, intensive hurricanes, flooding, larger wildfires, extreme heat temperatures and drought can lead to devastating consequences for the society and its infrastructure [1]. At the same time, the society has become more dependent on the reliable electricity infrastructure in order to function normally.

Historically, the power system has been designed and operated with the assumption that the system will not be exposed to high-impact, low-probability events, such as extreme weather conditions [2]. However, the effect of these events can lead to total system collapse.

According to the studies in [3], [4] and [5], the ascending trend of blackouts in recent years suggests that today's power system is becoming increasingly vulnerable to severe weather and puts an accent on an emerging issue that deals with power system resilience. The power system resilience can be defined as the ability of the system to withstand (low-frequency, high-impact) disasters efficiently, while ensuring the least possible interruption in the supply of electricity, sustaining critical social services, and enabling a quick recovery and restoration to the normal operation state [6].

Quantifying resilience is not a straightforward process since resilience is a multidimensional, dynamic concept with several intrinsic complexities [3]. However, quantifying resilience is necessary to evaluate the effectiveness of the resilience strategies and update them if necessary. There are numerous resilience metrics, but quite often they capture only one or few dimensions of resilience.

For example, studies in [2] and [7] evaluate resilience through simulation, more specifically by setting a Monte-Carlo simulation model and assessing reliability indices EENS (Expected Energy Not supplied), LOLF (Loss of Load Frequency) and LOLE (Loss of Load Expectation). In [7] different case scenarios are compared, where system is exposed to different wind levels (normal, high and extreme), while in [2] by using a fragility model of the Great Britain power transmission system, the failure probabilities of real-time impact of severe weather, with focus on wind, are determined. It has been shown that with an increased wind level, the frequency and the duration of customer interruption increases significantly [7]. This can be reflected as an actual behavior of the power system when exposed to weather conditions, i.e., robust to a certain level, but vulnerable to extreme conditions. Moreover, in [2] it is shown that the power system resilience is directly linked to the wind speed. With a wind speed lower than 30 m/s, the British power system is robust. However, when the wind speed exceeds 30 m/s, a sharp and nonlinear increase of both EENS and LOLF is obtained. At a wind speed of 60 m/s, EENS is equal

Selection and peer-review under responsibility of the scientific committee of the 13_{th} Int. Conf. on Applied Energy (ICAE2021).

to nearly 700 GWh/week and LOLF is close to 0.24 occurrences/week. However, the wind speeds assessed in [2] are quite high (see Table I), and the question is would the results of the simulation coincide with the real-time events?

In [8], a vulnerability analysis of power distribution system co-owned by two distribution companies in Sweden is performed based on real outage data obtained from 2001 to 2008. The outage data and hourly weather data for affected areas are collected. The study shows that about 20% of all outages that lasted for more than 12 hours have a direct link to major weather events, such as storm. As the wind speed reaches more than 7.9 m/s, the risk of having outages that last for more than 12 hours increases significantly. However, the speed of 7.9 m/s is a very low threshold to be assessed. Further analysis shows that the combination of strong wind and heavy snow is very critical to the power system resilience. However, this study only covers a small part of the Swedish power system and a conclusion regarding the whole Swedish power system could not be obtained.

2. AIM OF THE STUDY

The aim of this paper is to investigate how bad weather, such as wind, snowfall and lightning, has affected the Swedish power system from 2015 to 2019. The main idea is to analyze the data and start the identification of the weak points within the power system. Moreover, this paper sets up the basis for the future work that includes developing strategies for the network resilience improvement. Input data is obtained from the Swedish energy companies (Energiföretagen Sverige) [9]. The input data includes unplanned outage reports provided by all 171 distribution companies within Sweden. The number of unplanned outages per year was on average 54 167 (Table II). Among all these unplanned outages, outages related to bad weather are extracted. Weather measurements, such as wind speed, rainfall etc., are obtained from SMHI (Swedish Meteorological and Hydrological Institute) [10]. All the gathered data of unplanned disturbances from the Swedish power system are compared and analyzed. To analyze the collected data, the whole period is divided into smaller sub-periods over one year. For each year, the cause, duration and number of customers affected is extracted and compared. In some sense, this study can be seen as the continuation of the study performed in [8], following weather conditions within Sweden, but with a much bigger scope, and significantly more data.

3. RESULTS AND ANALYSIS

The total amount of disturbances due to weather conditions varies from year to year and is hard to predict. On average, around 21% of each year's unplanned disturbances are a direct result of weather conditions (Table II). Fig. 1 illustrates the total number of interruptions and the number of interruptions caused by bad weather each year. There are two years that have more disruptions than others, 2015 and 2019. In both 2015 and 2019, Sweden was hit by several storms with average speed above 30 m/s [11]. To show the effects of certain wind speeds, the Beaufort Wind Scale is shown in Table I, which presents the land conditions with respect to wind speed. With an average wind speed of 30 m/s there will be considerable structural damage or even violent destruction. The amount of days with wind speed larger than 25 m/s also peaked in 2015 [12], which can explain the large number of fault duration and customers affected, as shown in Fig. 2 and 3, respectively. According to DARwin statistics related to the outages within Sweden (Driftstörningsstatistik) [13], there is a significant increase in SAIDI due to weather conditions for years 2015 and 2019. In 2015 SAIDI is approximately 130 min/year and in 2019 163 min/year, which is in line with the results obtained here.

Table I: Beaufort wind scale [14]

Beaufort number	Description	Wind speed	Land conditions
0	Calm	0 m/s (<1 mph)	Smoke rises vertically
1	Light air	0.5-1.5 m/s (1-3 mph)	Smoke drifts with air, weather vanes inactive
2	Light breeze	2-3 m/s (4-7 mph)	Weather vanes active, wind felt on face, leaves rustle
3	Gentle breeze	3.5-5 m/s (8-12 mph)	Leaves and small twigs move, light flags extend
4	Moderate breeze	5.5-8 m/s (13-18 mph)	Small branches sway, dust and loose paper blows about
5	Fresh breeze	8.5-10.5 m/s (19-24 mph)	Small trees sway, waves break on inland waters
6	Strong breeze	11-13.5 m/s (25-31 mph)	Large branches sway, umbrellas difficult to use
7	Moderate gale	14-16.5 m/s (32-38 mph)	Whole trees sway, difficult to walk against wind
8	Fresh gale	17-20 m/s (39-46 mph)	Twigs broken off trees, walking against wind very difficult
9	Strong gale	20.5-23.5 m/s (47-54 mph)	Slight damage to buildings, shingles blown off roof
10	Whole gale/Storm	24-27.5 m/s (55-63 mph)	Trees uprooted, considerable damage to buildings
11	Violent storm	28-31.5 m/s (64-73 mph)	Widespread damage, very rare occurrence
12	Hurricane	over 32 m/s (over 73 mph)	Violent destruction

Table II: Outage statistic in Sweden between 2015-2019

Year	Total number of outages	Weather related outages	Percentage of weather related outages
2015	56 839	15 219	27%
2016	47 104	8 503	18%
2017	50 668	7 908	16%
2018	57 599	12 677	22%
2019	58 626	14 268	24%
Average	54 167	11 715	21%

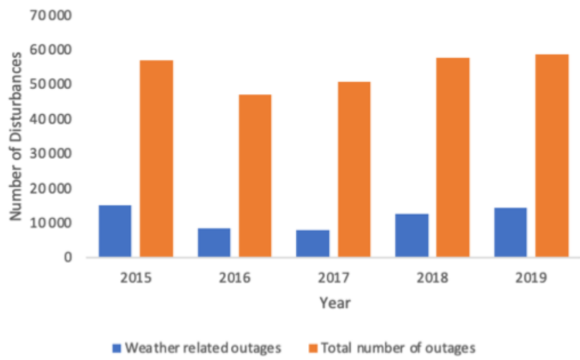

Fig 1: Total cases of disturbances between 2015-2019

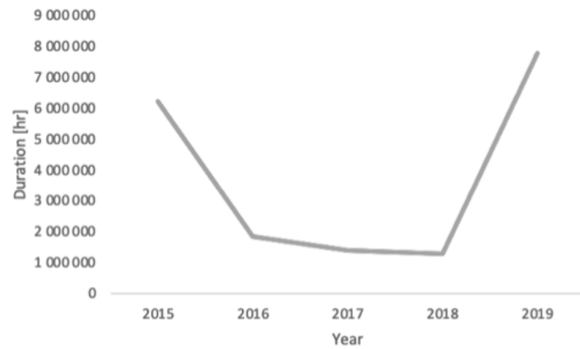

Fig 2: Total duration of disturbances due to bad weather between 2015-2019

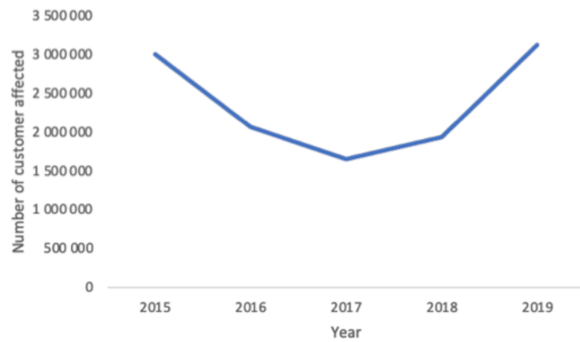

Fig 3: Total number of customers affected due to bad weather between 2015-2019

If we compare this analysis with the analysis on the Swedish power system presented in [8], similarly in [8] 20% of all unplanned outages are due to major weather events and wind can be interpreted as one of the leading cause for outages. Moreover, Sweden was hit by several storms during both study periods. During the period from 2001-2008, there were only two storms, among which Gudrun (2005) caused the highest number of outages, with the average wind speed of 33 m/s, which resulted in over 75 million cubic meter of trees blown down in Sweden alone [11]. During this study period of 5 years (2015-2019), the frequency of storm have increased significantly, with the total of 10 storms, where the highest average speed was 42 m/s in 2019 (see Table III). This increasing frequency in storms definitely puts a lot of stress on the resilience of the Swedish power system.

In 2019, an increased number of lightning strikes also contributed to a higher number of interruption cases. According to SMHI, the number of lightning discharges increased notably from 2015 to 2019 which can be seen in Fig. 4. In 2019, it was more common to face lightning discharges in the southern part of Sweden than in the northern part. As most of the customers in Sweden are located in the southern part, the total number of customers affected by lightning was the highest for the observed 5 year-period [15]. The curve of affected customers caused by lightning is shown in Fig. 5.

Table III: Storms in Sweden between 2015-2019 [11]

Storm	Date	Maximum wind speed [m/s]	Average wind speed [m/s]
Alfrida	2019-01-01	38.5	29.4
Jan	2019-01-10	49.7	42.0
Julia	2019-02-16	43.5	37.0
Mats	2019-02-24	39.0	32.5
Urd	2016-12-26	36.3	27.2
Helga	2015-12-04	37.9	29.3
Gorm	2015-11-29	39.8	29.6
Freja	2015-11-08	38.0	27.7
Ole	2015-02-06	43.0	39.0
Egon	2015-01-10	40.0	30.0

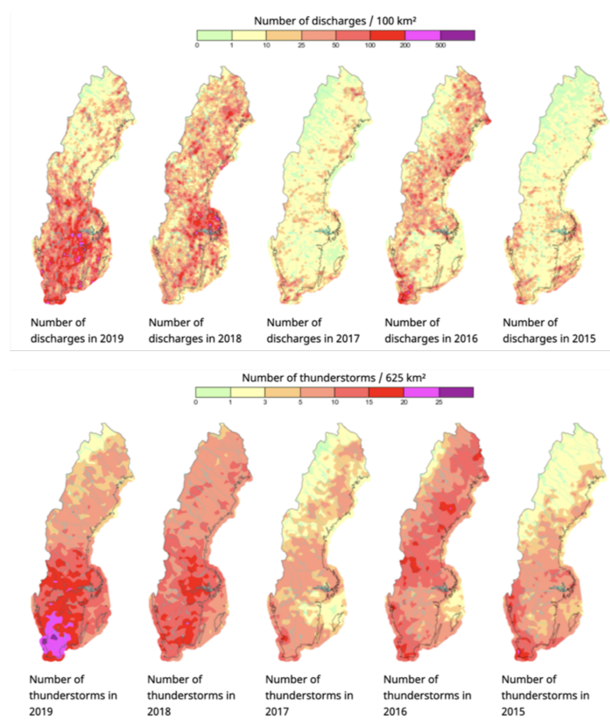

Fig 4: Number of lightning strikes and thunderstorms pre year between 2015-2019 [15]

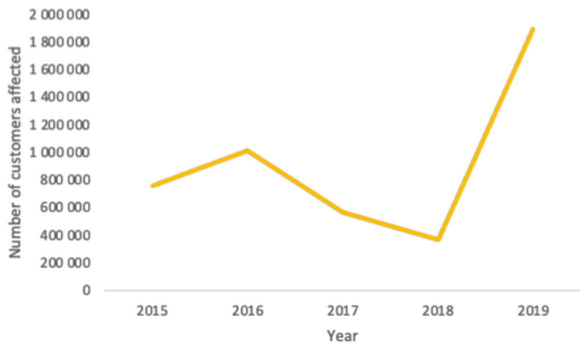

Fig 5: Total number of customers affected by lightning

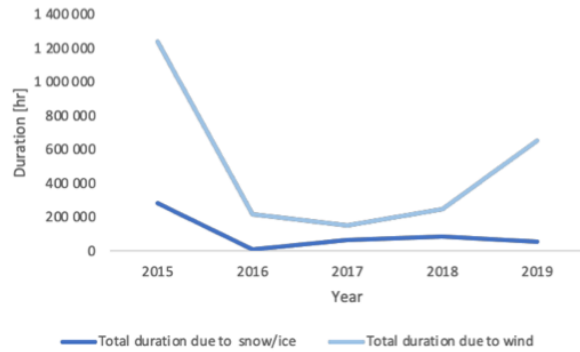

Fig 6: Fault duration time due to heavy snow and wind

The exact position of an outage due to bad weather conditions can be hard to locate, as storms and heavy snowfall affect bigger areas and can cause several faults at once. The fault duration due to such weather phonemes can also increase if the affected component is unknown, since it takes longer time to locate it. Fig. 6 illustrates the duration time of heavy snowfall and wind over the studied period. Of all conditions related to bad weather, wind and snowfall are the two conditions that cause the longest outage time.

Fig. 7 illustrates the number of outages due to heavy rainfall per year in the Swedish power system. For the studied period of five year, each year has less than 140 cases, which represents less than 1% of total disturbances caused by bad weather in that year. SMHI shows that the amount of rainfall from 2015 to 2019 is quite stable and does not fluctuate much. The average is around 600-800 mm per year with the highest numbers in 2015 and 2019 (Fig. 8) [16]. Because of the rare outages, it is possible to argue that the Swedish power system is quite resilient to the heavy rainfall.

In many cases, the weather conditions may not cause a direct failure in the power system. Rather, they can affect the surroundings of the infrastructure, such as tree fall due to heavy wind or snow, that can indirectly lead to a failure. Statistics for tree fall related faults are shown in Fig. 9. In total, indirect cases stand for around 50% of total weather disturbances per year which is, no arguably, the number one cause of weather-based outages.

Different parts of the power system are affected differently by the weather. Fig. 10 shows the number of cases on each level of the distribution system. The low voltage parts of the distribution system are more prone to the failure than the high voltage ones. In 2018, outages originated in the 0.4 kV system covered alone for over 50% of unplanned weather-based disruptions, while the ones originated in 132 kV system covered less than 1.4% of total cases.

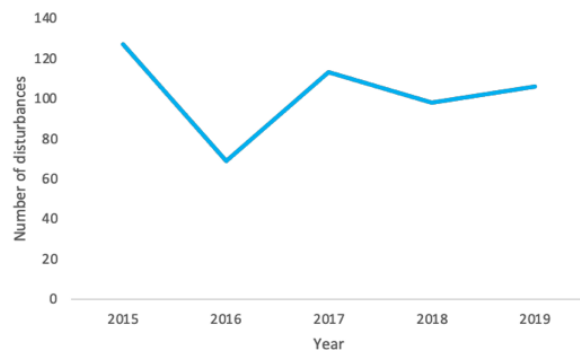

Fig 7: Total number of disturbances due to rain

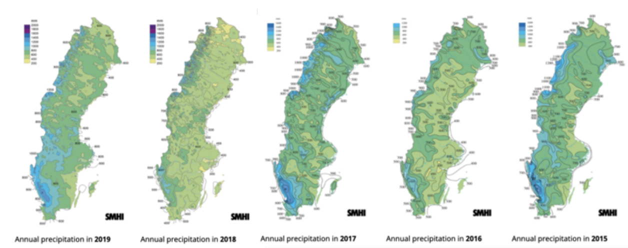

Fig 8: Precipitation per year between 2015-2019 [16]

Fig 9: Faults due to tree fall

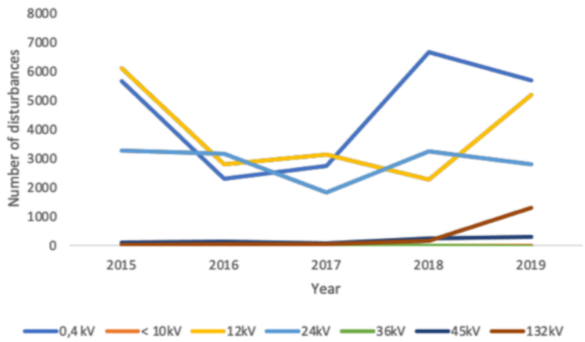

Fig 10: Fault location of the distribution system

Fig. 11 illustrates the disturbances distributed over each month every year. The peak of outages occurs in January, June and December and drops in May and October. Strong wind and heavy snow occur in January and December, while thunderstorms and lightning are mostly reserved for June. With a higher frequency of disturbances during these months, it may not be a good idea to have planned maintenance in January, June or December, since planned maintenance during these months can lead to longer and more frequent outages. On the other hand, the most suitable time for planned maintenance would be in months with the least weather-based outages, such as May or October.

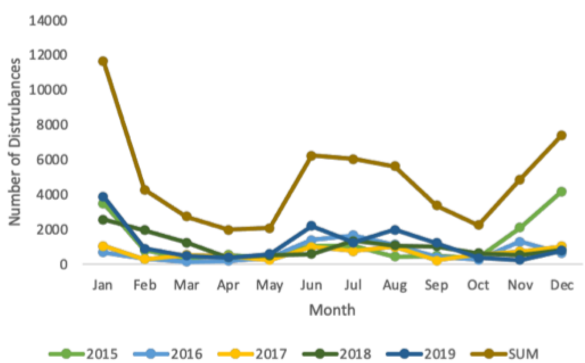

Fig 11: Total number of disturbances during each month

4. DISCUSSION

Assessing the power grid's resilience against severe wind conditions can differ greatly, depending on the choice of assessing method. Using a simulation method, as presented in [2] and [7], the power system can withstand higher levels of wind speed, compared to real-time events and the system based on the real data. As the simulation method usually does not take into consideration indirect faults and the management of vegetation of surrounding areas, this can explain the more optimistic results obtained from the simulation-based analysis. However, nearly 50% of weather-based faults are due to tree falls, which highlights the importance of the real data analysis. Furthermore, the age and the condition of the components are essential factors that need to be considered when analyzing the system resilience, as older components can have more difficulties to withstand a bad weather event than the new ones.

Many of the indirect disturbances can be prevented with better maintenance around the power system, for example regular checks on the vegetation around overhead lines and substations. Another more expensive but effective way to avoid damaging effects of tree falls is to replace overhead lines with underground cables. It is important for larger distribution companies to have a vegetation management, as they are more prone to indirect disturbances than smaller distribution companies. The data also show that it is harder for larger companies to navigate the failure source, which increases the respond and duration time during an outage.

Based on the results, the frequency and the duration of faults is higher in the lower voltage parts compared to the higher voltage areas. Lower voltage parts supply less customers, and thus, they are not secured enough as higher voltage parts where more customers are connected. To achieve better resilience, the low voltage distribution system may need more proactive maintenance or reinforcement of certain grid parts.

5. CONCLUSION

In the fight with climate change, enhancing the power system resilience against bad weather should be one of the major aim of utilities, since every modern society is highly dependent on the power system infrastructure. This study investigates how bad weather, such as wind, snowfall and lightning, has affected the Swedish power system from 2015 to 2019. It has been shown that the bad weather conditions cover on average 21% of the unplanned disturbances. Direct cases of weather affecting power system, such as wind and lightning, are the conditions that cause most outages. Many weather events also affect the surroundings of the power system infrastructure, which shows the importance of the maintenance in the power system. Tree falls due to wind and heavy snowfall are indirect cases that cover around 50% of all weather-based disturbances. This analysis sets up the basis for the future work that involves identifying weak points in the system and developing strategies for the network resilience improvement against bad weather conditions.

ACKNOWLEDGEMENT

The authors thank SweGRIDS, the Swedish Centre for Smart Grids and Energy Storage, for funding the project. Moreover, the authors thank Matz Tapper from Energiföretagen Sverige for providing valuable data and practical information for this project.

REFERENCE

[1] Earthjustice. How Climate Change is Fueling Extreme Weather. 2021; Available from: https://earthjustice.org/features/how-climate-change-is-fueling-extreme-weather.

[2] Panteli, M., et al., Power system resilience to extreme weather: fragility modeling, probabilistic impact assessment, and adaptation measures. IEEE Transactions on Power Systems, 2016. 32(5): p. 3747-3757.

[3] Panteli, M. and P. Mancarella, The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience. IEEE Power and Energy Magazine, 2015. 13(3): p. 58-66.

[4] Bompard, E., et al., Classification and trend analysis of threats origins to the security of power systems. International Journal of Electrical Power & Energy Systems, 2013. 50: p. 50-64.

[5] Afzal, S., et al., State-of-the-art review on power system resilience and assessment techniques. IET Generation, Transmission & Distribution, 2020. 14(25): p. 6107-6121.

[6] Raoufi, H., V. Vahidinasab, and K. Mehran, Power systems resilience metrics: A comprehensive review of challenges and outlook. Sustainability, 2020. 12(22): p. 9698.

[7] Panteli, M. and P. Mancarella, Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events. IEEE Systems Journal, 2015. 11(3): p. 1733-1742.

[8] Wallnerstrom, C.J. and P. Hilber, Vulnerability analysis of power distribution systems for cost-effective resource allocation. IEEE Transactions on power systems, 2011. 27(1): p. 224-232.

[9] Om Energiföretagen Sverige. 2021; Available from: https://www.energiforetagen.se/om-energiforetagen-sverige/.

[10] SMHI. SMHI: Väder Väderprognoser Klimat- Vädertjänster i Sverige. 2021; Available from: https://www.smhi.se.

[11] SMHI. Stormar i Sverige. 2020; Available from: https://www.smhi.se/kunskapsbanken/meteorologi/stormar-i-sverige-1.5770.

[12] SMHI. Klimatindikator - geostrofisk vind. 2019; Available from: https://www.smhi.se/data/meteorologi/vind/klimatindikator-geostrofisk-vind-se-och-ladda-ner/1/n25.

[13] Tapper, M. Tech. rep. Energiföretagen, 2019. 2020; DARWin Driftstörningsstatistik 2019.]. Available from: https://www.energiforetagen.se/statistik/elstatistik/leveranssakerhetdarwin/darwin-arsstatistik/.

[14] NERACOOS. Beaufort Wind Scale. Available from: http://gyre.umeoce.maine.edu/data/gomoos/buoy/php/variable_description.php?variable=wind_2_speed.

[15] SMHI. Månads-, årstids- och årskartor. 2019; Available from: https://www.smhi.se/data/meteorologi/kartor/aska-antal-urladdningar/ar/.

[16] SMHI. Månads-, årstids- och årskartor - Årsnederbörd. 2020; Available from: https://www.smhi.se/data/meteorologi/kartor/arsnederbord.

