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Published in:
SUSTAINABILITY

DOI:
[10.3390/su9020230](https://doi.org/10.3390/su9020230)

Published: 01/01/2017

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Gündüz, N., Küfeoğlu, S., & Lehtonen, M. (2017). Impacts of natural disasters on swedish electric power policy: A case study. *SUSTAINABILITY*, 9(2), Article 230. <https://doi.org/10.3390/su9020230>

Article

Impacts of Natural Disasters on Swedish Electric Power Policy: A Case Study

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Academic Editors: Jenny Palm and Marc A. Rosen

Received: 23 December 2016; Accepted: 4 February 2017; Published: 8 February 2017

Abstract: The future of climate and sustainable energy are interrelated. Speaking of one without mentioning the other is quite difficult. The increasing number of natural disasters pose a great threat to the electric power supply security in any part of the world. Sweden has been one of the countries that have suffered from unacceptably long blackouts. The tremendous outcomes of the power interruptions have made the field of the economic worth of electric power reliability a popular area of interest among researchers. Nature has been the number one enemy against the supply security of the electricity. This paper introduces a recent and thorough electric power reliability analysis of Sweden and focuses on the country's struggle against climate change-related natural disasters via updating the country's electric power policy to improve its service quality. The paper highlights the Gudrun storm of 2005 as a case study to demonstrate the severe impacts of extreme weather events on the energy systems. The economic damage of the storm on the electric power service calculated to be around 3 billion euros.

Keywords: reliability; policy; climate; storm; power; interruption; Sweden

1. Introduction

Energy is a vital part of life. By being easy to produce and easy to convert to other forms of energy, the significance of electric energy has been increasing from the date of its first usage. As years pass by electric power is penetrating into almost every aspect of daily life. This makes societies and the economies more dependent on electric power. The total electric power consumption in the world has been increasing considerably for the last 60 years [1]. The tremendous outcomes of the power interruptions have made the field of economic worth of electric power reliability a popular area of interest among the researchers. Nature events have been the biggest threat against the supply security of the electricity [2–4]. Experiences show that both the number and the duration of extreme weather events have increased substantially over the last decades. Environmental scientists indicate that the climate change is a major factor that increases the frequency and the intensity of these events [5]. The consequences of natural disasters are severe for the environment, the economy, and people's wellbeing. Different parts of the world are prone to different types of extreme weather events. The central European flood of 2013 lasted almost a month and caused extensive damage to the ecosystem and to the communities. It also led to serious damages on the electric power system resulting in long lasting blackouts. Germany experienced the highest losses due to flooding, with a cost of 12 billion euros, where total losses in the region reached 17 billion euros [6]. The flooding in Toronto, Canada, in 2013 disrupted the power reliability and about 70,000 customers experienced long power interruptions [7]. On the other hand, in 2005, the hurricane Katrina hit the United States and about 2.7 million customers lost electric power [8]. In 2012, the hurricane Sandy caused severe damages in the United States and Canada and up to 9.3 million electric power customers experienced power

outages [9]. After the disaster, the electric power infrastructure repairing costs reached 3.5 billion dollars [9]. In December 2013, heavy storms hit the United Kingdom. The Environment Agency, Met Office, reported that England had been suffering from the wettest winter seen in 250 years [10]. Due to the storms, in the United Kingdom and Ireland, about 750,000 customers experienced power outages [11]. In 2008, extreme ice storms caused substantial damages in China. The long and heavy ice formations on the Chinese power grid led to the collapse of thousands of transmission towers and hence triggered cascading interruptions [12]. Almost 200 million people were not able to reach electric power service and the direct costs of these interruptions exceeded 2.2 billion dollars [12].

This paper introduces a recent and thorough electric power reliability analysis of Sweden and focuses on the country's struggle against climate change-related natural disasters. It also presents a cost estimation of the consequences of the Gudrun storm of 2005 on electric power customers.

2. The Gudrun Storm of 2005 and Its Aftermath

The Swedish annual electric power consumption per person is one of the highest in the world [13]. Figure 1 illustrates a comparison of the electric power consumption per capita among several countries.

In accordance with the energy and climate goals of the European Union, Sweden has been taking measures in boosting the energy efficiency. Figure 1 presents the success of these policies by demonstrating the decrease in electric energy consumption per person for the last decade. However, it is clear that the global financial crises of 2008 played a major role in deteriorating the European economies, hence causing sharp decreases in the consumption of electric energy.

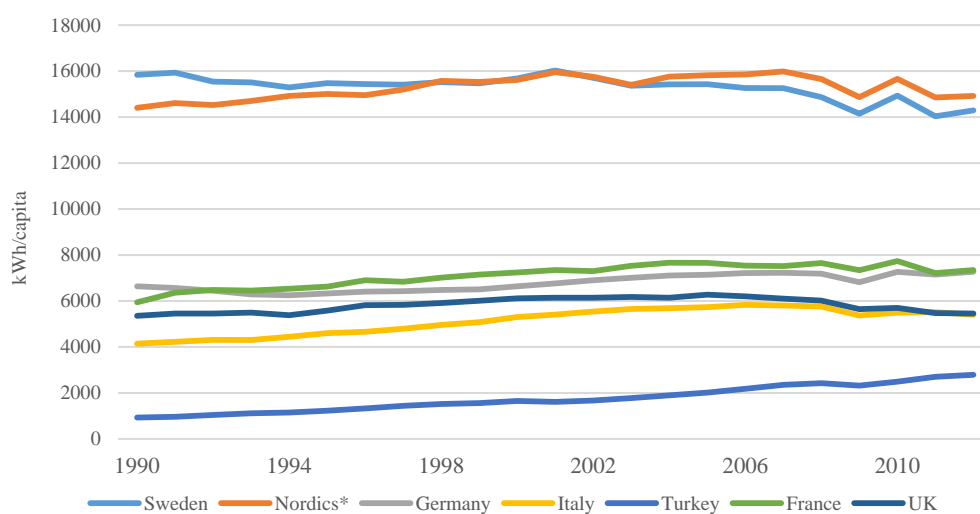


Figure 1. Yearly change of electric power consumption per capita in several countries [13]. * Finland, Sweden, Norway, and Denmark (Iceland excluded).

Thanks to its highly developed and robust electric power infrastructure, Sweden had been enjoying a high level of electric power security until the year 2005. In January 2005, the Gudrun storm hit Northern Europe, causing a substantial amount of destruction in Sweden, Denmark, Latvia, Lithuania, and Estonia. Sweden experienced the most severe losses. Around 730,000 customers experienced long-lasting power interruptions [14]. The electricity service restored within 24 h for almost half of the customers who lost power. Throughout the country, the interruption durations changed due to the changing usage of underground cables. The city areas were least affected thanks to the high degree of cabling. The outages in these places lasted up to several hours. On the other hand, since the power distribution heavily relies on aerial lines, the outages in rural areas persisted for up to 20 days [14]. The lines passing through forests were the main places where the damages occurred. The falling trees over power lines caused a considerable number of interruptions for Swedish

customers. Falling trees on the lines and collapsing poles harmed almost 30,000 km of distribution lines [15]. Fortunately, the storm did not create excessive damages to the transmission lines. The storm did not largely affect the power generation capacity of Sweden [15]. Only 20% of the power capacity was lost due to the shutdown of four nuclear reactors and to the downscaling of one reactor [15]. In the case of storm-related power outages, the percentage of underground cables plays a crucial role in diminishing the economic and social outcomes of the events. Table 1 shows the types of the distribution lines and their average lengths belonging to 16 distribution system operators (DSOs) that were most affected by Gudrun [16].

Table 1. The distribution line types of 16 network operators [16].

	Distribution Lines in Affected Areas (Total)	Cable	Insulated Overhead Lines	Uninsulated Overhead Lines
Length (km)	142,631	68,593	23,193	50,845
Percentage (%)	100	48	16	36

Insulated overhead lines and especially uninsulated overhead lines were the main source of problems. The total cost of the hurricane with all direct and indirect impacts is not certain. However, the estimations tell that the interruption losses incurred at the society extend from 1.6 to 2.1 billion Swedish Krona (SEK). In addition to this, the DSOs reported enormous monetary losses as well. When summed up, the total cost of the Gudrun storm related to blackouts only reached a figure from 4 to 5 billion SEK [8]. On average, during January 2005, 1.0 SEK was equal to 0.11 euros [17]. This means, storm-related outages had a cost of 400–500 million euros to the Swedish society. Table 2 presents the estimations of the DSO outage costs during Gudrun [16].

Table 2. Cost estimations by network operators [16].

	Loss of Supply	Clearance, Repair and Restoration	Compensations for Loss of Supply	Other Costs	Total
SEK million	53.62	1537.32	613.70	132.05	2344.78
EUR ¹ million	5.90	169.11	67.51	14.53	257.93
Share (%)	2	66	26	6	100

¹ 1 SEK was taken to be equal to 0.11 EUR according to the European Central Bank, January 2005 exchange rate [17].

The clearance, repair, and restoration efforts held the lion's share of the losses. The sum of utility compensations comprises 26% of the total losses. The Swedish government proposed the first customer compensation scheme during 2001. However, this proposal was not made into law. According to this proposal, if a single power outage event extends a predefined duration, then the DSO is to pay back to the customer a certain percentage of the customer's annual electricity delivery fee as a penalty. Table 3 summarizes the proposal of 2001.

Table 3. The proposed outage compensation scheme, 2001 [18].

Outage Time	Compensation
(h)	(SEK)
$12 < t < 24$	500
$24 < t < 48$	1000
$48 < t < 72$	3000
$72 < t$	6000

After the Gudrun storm, in October 2005, the Swedish government updated the electricity law and made the compensation scheme of 2001 compulsory for the DSOs [18]. Another update came

during 2014 [19]. Table 4 depicts the new plan, which introduces longer interruption intervals with corresponding higher penalties for the network operators.

Table 4. The compensation scheme by Swedish electricity law [19].

Outage Time	Percentage of Annual Costs Compensated	Minimum Amount of Compensation
(h)	(%)	(SEK)
$12 < t < 24$	12.5	500
$24 < t < 48$	37.5	1000
$48 < t < 72$	62.5	3000
$72 < t < 96$	87.5	6000
$96 < t < 120$	112.5	4500
$120 < t < 144$	137.5	5400
$144 < t < 168$	162.5	6300
$168 < t < 192$	187.5	7200
$192 < t < 216$	212.5	8100
$216 < t < 240$	237.5	9000
$240 < t < 264$	262.2	9900
$264 < t < 288$	287.5	10,800
$288 < t$	300	11,700

The electricity law states that, under certain limited conditions, the electricity consumer is not entitled to earn compensation for power interruption, despite a service break. This applies under the following states [19]:

- Interruption is due to the negligence of the electricity user.
- The electricity is interrupted because of electrical safety reasons or to preserve supply security and reliability.
- Interruption is due to a barrier outside the network owner's control.
- Interruption is attributable to the fault in the grid.

3. The Electric Power Reliability in Sweden

System Average Interruption Duration Index (*SAIDI*) and the System Average Interruption Frequency Index (*SAIFI*) are commonly used to interpret the reliability, where *SAIDI* (in hours) and *SAIFI* are defined as

$$SAIDI = \frac{\text{total duration of sustained interruptions in a year}}{\text{total number of customers}} (h) \quad (1)$$

$$SAIFI = \frac{\text{total number of sustained interruptions in a year}}{\text{total number of customers}} \quad (2)$$

Figure 2 shows the changes in *SAIDI* outage hours in Sweden between 2005 and 2014. The interruptions here are the total planned and unplanned interruptions lasting more than three minutes [20].

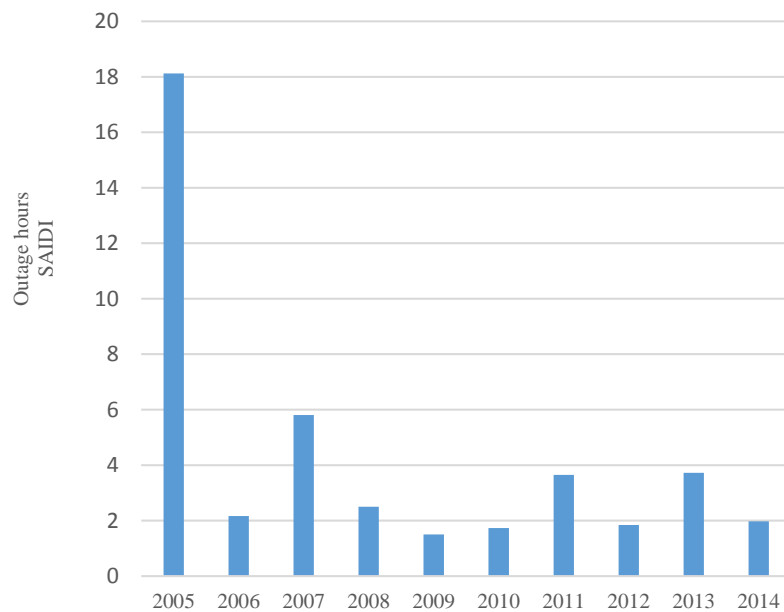


Figure 2. SAIDI outage hours in Sweden, 2005–2014 [20].

The characteristics of the outages show that the majority of the events were unexpected (or unplanned) events. Figure 3 illustrates the characteristics of the power interruptions in Sweden from 2007 to 2014.

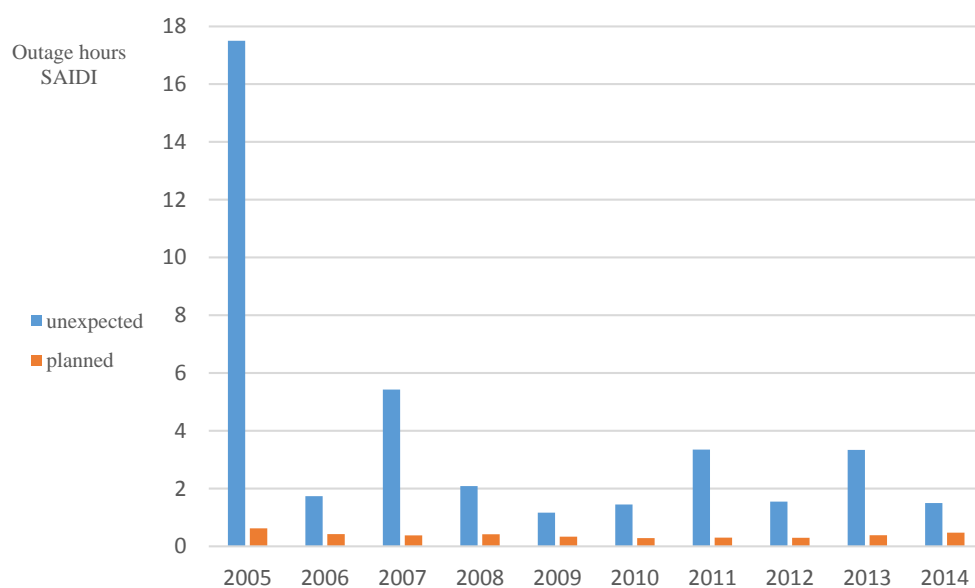


Figure 3. Distribution of the unexpected and planned outages in Sweden, 2005–2014 [20].

The causes for the interruptions at Figure 4 indicate that, during 2005, almost 50% of all outages in Sweden resulted from nature events.

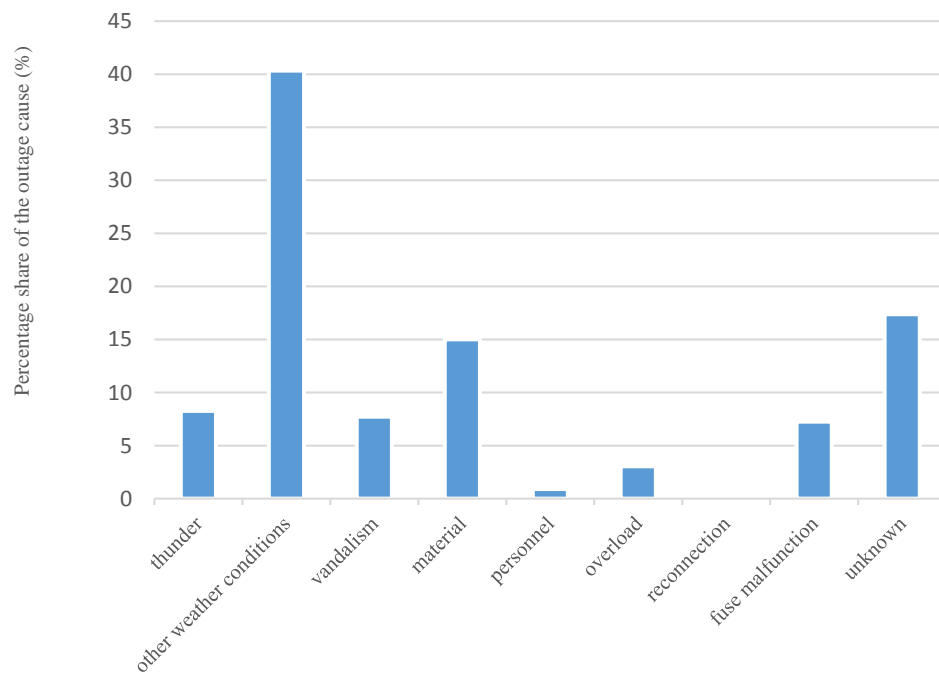


Figure 4. Causes for the power interruptions in Sweden during 2005 [20].

The sources of the interruptions show that the Swedish DSOs have overcome the shock of Gudrun and strengthened their supply security after the year 2005 [20]. Figure 5 presents the summary of the distribution of the outage causes during 2007–2014. The reasons for interruptions have been regrouped as nature, human, operation, and unknown.

- nature: thunders and other weather conditions
- human: personnel and vandalism
- operation: material, overload, reconnection, and fuse malfunctioning
- unknown

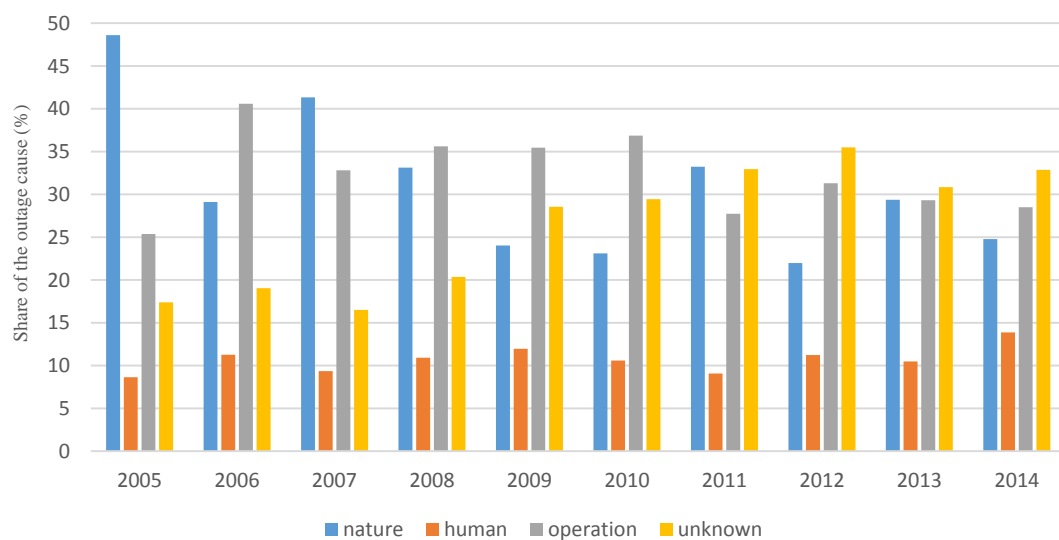


Figure 5. Share of the causes for the power interruptions in Sweden, 2007–2014 [20].

One alarming observation is that, while the share of nature-related events is decreasing almost gradually, there is a considerable increase in the outages with unknown causes. In order to make a comparison, Figure 6 summarizes the reliability performance of Finland. The Finnish power system has mainly been suffering from nature events, where the unknown interruption reasons are negligible [21]. The high interruption hours in 2010, 2011, and 2013 are due to the harsh storms that hit Finland and caused substantial damage to the Finnish electricity customers [21].

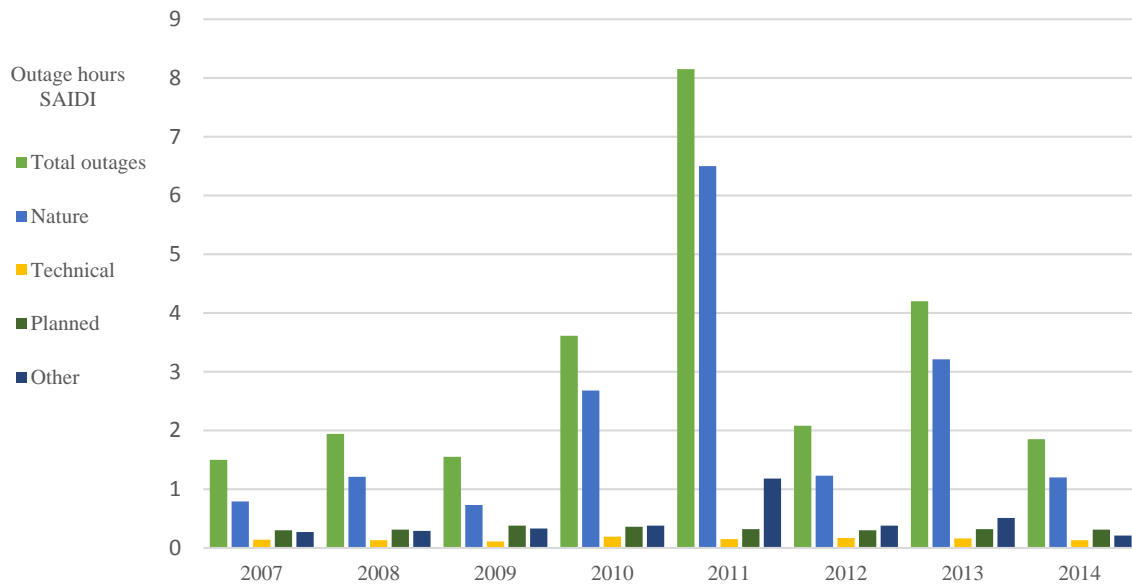


Figure 6. Outage hours and the causes for the power interruptions in Finland, 2007–2014 [21].

Calculating the Costs of Power Interruptions

Estimation of the customer interruption costs (CIC) is a challenging task for the researcher. There have been numerous studies to introduce a credible and objective methodology to solve the problem. The extensive review paper [22] compiles the significant studies that focus on the phenomena of the electric power reliability worth and customer interruption costs published since the year 1990. The paper clearly demonstrates that calculating the real monetary value of the continuous electricity supply is a highly tedious task. Different customer segments require distinct evaluation techniques to find out the worth of the electric power reliability. On the other hand, the Energy Market Authority of Finland prefers to evaluate the disadvantages caused by long outages by calculating the customer interruption costs according to Equation (3) [23].

$$CIC_{t,k} = \left(\frac{OD_{unexp,t} \times h_{E,unexp} + OF_{unexp,t} \times h_{W,unexp,t} + OD_{plan,t} \times h_{E,plan} + OF_{plan,t} \times h_{W,plan}}{OD_{unexp,t} \times h_{E,unexp} + OF_{unexp,t} \times h_{W,unexp,t} + OD_{plan,t} \times h_{E,plan} + OF_{plan,t} \times h_{W,plan}} \right) \times \frac{W_t}{T_t} \times \frac{CPI_{k-1}}{CPI_{2004}} \quad (3)$$

where

$CIC_{t,k}$: monetary worth of the power interruptions to the DSO's customers in year t in the value of money in year k , euros;

$OD_{unexp,t}$: customer's average annual unexpected outage time weighted by annual energies in the year t , hours;

$h_{E,unexp}$: value of the unexpected outages to the customer in the 2005 value of money, euros/kWh;

$OF_{unexp,t}$: customer's average annual unexpected outage number weighted by annual energies in the year t , numbers;

$h_{W,unexp}$: value of the unexpected outages to the customer in the 2005 value of money, euros/kW;

$OD_{plan,t}$: customer's average annual planned outage time weighted by annual energies in the year t , hours;

$h_{E,plan}$: value of the planned outages to the customer in the 2005 value of money, euros/kWh;

$OF_{plan,t}$: customer's average annual planned outage number weighted by annual energies in the year t , numbers;

$h_{W,plan}$: value of the planned outages to the customer in the 2005 value of money, euros/kW;

W_t : the customer's amount of energy consumption in the year t , kWh;

T_t : the total number of hours in a year;

CPI: Consumer Price Index.

Table 5 summarizes the necessary statistical data for the outage cost calculation.

Table 5. Power interruption, electricity consumption, and consumer price index statistics of Sweden between 2005 and 2015 [20,24,25].

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
SAIDI unexpected (h)	17.48	1.73	5.43	2.09	1.17	1.45	3.35	1.55	3.34	1.50	2.17
SAIDI planned (h)	0.62	0.42	0.37	0.42	0.34	0.29	0.30	0.29	0.39	0.47	0.33
SAIFI unexpected	1.49	1.22	1.46	1.33	1.12	1.42	1.81	1.48	1.48	1.42	1.28
SAIFI planned	0.22	0.22	0.24	0.30	0.16	0.16	0.16	0.14	0.16	0.18	0.15
Consumer Price Index	100	101.36	103.61	107.21	106.87	108.22	111.07	112.05	112	111.8	111.75
Electricity consumption (TWh)	135	135	136	133	128	137	129	132	129	125	125

Sweden and Finland are in the Nord Pool power market and hence the retail electricity prices are quite close to each other. Since the value of end user electricity and the consumer characteristics in Sweden and Finland are quite similar, at the calculation stage, the h values defined by the Energy Market Authority of Finland have been used. Table 6 demonstrates the h values.

Table 6. Prices in 2005 values for calculation of the customer interruption costs [23].

	$h_{E,unexp}$ (€/kWh)	$h_{W,unexp}$ (€/kW)	$h_{E,plan}$ (€/kWh)	$h_{W,plan}$ (€/kW)
Value	11	1.1	6.8	0.5

The Swedish network operators reported their direct losses due to power interruptions to be around 257 million euros in 2005 during the Gudrun storm. According to the calculations with Equation (3), the total costs of all power interruptions in the entire year of 2005 were about 3 billion euros. This is reasonable when all direct and indirect impacts of power outages are taken into account. Furthermore, the comprehensive report written after the infamous New York City blackout of 1977 show that the monetary worth of the indirect impacts of outages are much higher than the direct ones [26]. Table 7 shows the calculated CIC's in Sweden from 2005 to 2015.

Table 7. Customer Interruption Costs in Sweden between 2005 and 2015.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
CIC (M€)	2996	324	992	404	223	298	638	317	636	293	406

4. Discussion

The significance of energy and climate change topics have increased in many folds after the United Nations Climate Change Conference Paris 2015 and the European Union's 2020, 2030, and 2050 energy and climate goals. The frequency of the climate change-related extreme weather events has increased

considerably for the last couple of decades. Therefore, investigating the consequences of these events on the energy systems is imperative. Sweden is a developed country sharing accurate and transparent data for research purposes. The protection of the customers' right is of vital concern. These facts make Sweden a proper place to study the impacts of natural disasters on electric power reliability. Figure 3 demonstrates the tremendous impacts of the Gudrun storm on Swedish electric power system. An annual outage hour of 18 h was a record high and after the storm, the government decided to go through vast transformation plans for the Swedish electric power infrastructure. In 2005 alone, the power outages costed almost 3 billion euros to the Swedish society. To strengthen the security of the Swedish power delivery system, nearly 5 billion euros were spent [27]. Tables 3 and 4 present the policy changes of the Swedish government after the storm in 2005. The customer compensation scheme was updated to protect the consumers more by increasing the penalties in case of power outages. On the other hand, serious infrastructure boosting attempts started as a solution to increase the supply security in the country.

5. Conclusions

The cost of the storm on electricity service reached 3 billion euros in Sweden in 2005. To avoid such a shocking incident, the majority of the sources were spent in laying cables and replacing aerial lines with underground cables. Figures 2 and 5 show the success of the program in reducing the total outage hours and weakening the impacts of harsh weather conditions on the electric power system. Nevertheless, Sweden is still performing poorer than many European states in power reliability. The country's annual average outage hour is higher than many of the European Union member states [28]. The country has been struggling against the same odds similar to her neighbor Finland [29]. There has not been such a major natural disaster in the region since 2005. The policy makers aim to improve the supply security in Sweden. Under the light of these, it is clear that there is more to do in protecting the Swedish electricity customers. The increasing share of the unknown causes of the power outages is an urgent matter for the authorities and for the DSOs. Widening the aerial transmission and distribution line corridors by de-vegetation is another viable precaution to decrease the adverse effects of the nature events on the electric power system.

Acknowledgments: This paper has been prepared as a part of the Smart Control Architecture for Smart Grids (SAGA) project at the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland.

Author Contributions: Niyazi Gündüz compiled the necessary data for the Gudrun storm and Swedish power interruptions and carried out statistical analysis to demonstrate the results. Sinan Küfeoğlu was responsible for the calculation of the customer interruption costs due to power outages. He employed Equation (1) and adapted it to the Swedish case. Matti Lehtonen contributed to the paper by providing information of the Finnish supply security.

Conflicts of Interest: The authors declare no conflict of interest.

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