Power outage related statistics in Sweden since the early 2000s and evaluation of reliability trends

Carl Johan Wallnerström
The Swedish Energy Markets Inspectorate (Ei)
Eskilstuna, Sweden
https://orcid.org/0000-0001-6882-3642

Maria Dalheim
Ei
Eskilstuna, Sweden
maria.dalheim@ei.se

Mihai Seratelius
Ei
Eskilstuna, Sweden
mihai.seratelius@ei.se

Tommy Johansson
Ei
Eskilstuna, Sweden
tommy.johansson@ei.se

***Abstract*—This paper presents statistics based on over 15 years of power outage related data in Sweden collected by the national regulatory authority (NRA). In the early 2000s, Sweden introduced its first economic incentive scheme regarding continuity of supply (CoS) for power distribution system operators (DSO). For this purpose, the NRA began to collect power outage data from each DSO on an aggregated level. A few years later, in 2005, a severe hurricane struck Sweden that highlighted the vulnerability of the Swedish power system, resulting in a new regulatory framework related to power outages. To be able to effectively monitor the CoS in Sweden, the NRA began in 2010 to collect data on power outages on a customer level. Since 2012 a new revenue cap regulation with economic CoS incentives was implemented with major revisions from 2016 and 2020 respectively.**

The amount of detailed data available enables the NRA to closely monitor the CoS in the Swedish power grid. As a result of the stricter rules on power outages, there have been major investments in more reliable power distribution systems over the past decade. A positive tendency can be seen even if the CoS fluctuates from year to year due to e.g. weather events. The CoS is slightly better for years with mild weather and the impact on the CoS is less negative for years with severe storms, even if it is still far from good enough. The aim of this paper is to publish statistics with some concluding remarks from the NRA. We believe that sharing our experiences from Sweden may be of value for others, e.g. when developing new laws and regulations. The paper also contributes by informing about available data related to Swedish power outages for others to use when comparing countries or developing probabilistic models.

Keywords—Data collection, Incentive schemes, Power distribution, Power system reliability, Power outages, Regulation, Risk analysis, Statistics

I. Introduction

The Swedish electricity market underwent a major reform in 1996. Since then, generation and trading of electricity has been exposed to competition. The transmission and distribution of electricity are however a natural and legal monopoly where it would be both economically and environmentally ineffective to have competing grid infrastructures. Consequently, the power system operation is separated from power generation and trade (i.e. unbundling).

In 2005, a severe hurricane struck Sweden (referred to as Gudrun or Erwin), causing outages for ~450 000 customers (>8 %), of which ~100 000 customers experienced an outage lasting for more than four days. This extreme event largely increased the focus on the importance of reliable energy supply. In 2006, new rules entered into force mandating distribution system operators (DSOs) to establish an annual risk and vulnerability analysis with an action plan and to compensate customers experiencing outages longer than 12 hours [1]. From 2011, outages longer than 24 hours are not tolerated by law and the national regulatory authority (NRA) have been given the right to define additional minimum requirements of the continuity of supply (CoS).

TABLE I. Definitions and Abbreviations

Indicator	Description
CAIDI	Customer Average Interruption Duration Index. The average time of an outage, i.e. SADI/SAIFI.
CEMI-X	Number of customers with X or more interruptions during a year divided by the total number of customers.
CoS	Continuity of Supply
DSO	Distribution system operator
Ei	The Swedish Energy Markets Inspectorate (the NRA)
ENS	Energy not supplied [kWh].
Mixed grid	10-20 customer per kilometer feeder in average
NRA	National regulatory authority
PNS	Power not supplied [kW], same as “Loss of load”.
Rural grid	Less than 10 customers per kilometer feeder in average
SAIDI	System Average Interruption Duration Index, the average interruption time per customer and year.
SAIFI	System Average Interruption Frequency Index, the average number of interruptions per customer and year.
SNI code	A classification of customers, based on the EU standard “Statistical Classification of Economic Activities in the European Community” (ofter reffered to as NACE)
TSO	Transmission system operator
Urban grid	More than 20 customer per kilometer feeder in average

TABLE I. provides definitions of CoS indicators and other definitions and abbreviations used in this paper.

Aggregated statistics on power outages has been collected from the DSOs since the early 2000s by the NRA. That statistics included indicators such as SAIDI (see TABLE I.) to be used in e.g. CoS incentive schemes. Sweden was relatively early with such power outage data collection by the NRA, although not the first example [2].The Institute of Electrical and Electronic Engineers (IEEE) established common definitions for standard reliability indexes, of which one is SAIDI [3]. To enable more closely monitoring of CoS followed by new legislations, the NRA began from 2010 to collect more detailed data on a customer level. The increased level of detail in the data also led to the possibility of developing a better CoS incentive scheme in the revenue cap regulation [4] and to publish annual reports of the CoS in

Sweden [5]. Recently the NRA begun a project of open data based on the EU PSI Directive [6]. The great amount of data is also a valuable source for national and international research and development.

The aim of this paper is to publish statistics based on the considerable amount of data collected from all Swedish DSOs during a relative long period of time, but also to share our reflection as an NRA of the increasing legal focus on CoS since the early 2000s. Experience from Sweden could be valuable for others when developing laws and regulations in the future. This paper also contributes by informing about available data related to Swedish power outages to use when e.g. comparing countries or developing probabilistic models.

II. Monitoring and Incentivizing CoS in Sweden

A. Short introduction to the Swedish power system

There are currently approximately 170 DSOs and one government owned transmission system operator (TSO) in Sweden. The TSO owns and operates all parts of the transmission system (220 and 400 kV). All other entities that operate power systems in Sweden are defined as DSOs. The DSOs are of varying size (from less than 1 000 to up to about a million customers) and have different ownership structures.

All DSOs have one or more so-called concessions (permissions) for the distribution of electricity, either for a defined geographical area up to a certain voltage level or for a specific line (often) at higher voltage levels. DSOs with at least one area concession are referred to as local DSOs (in some cases line concessions can be merged within the reporting unit of a local DSO), while reporting units of only line concession(s) are referred to as regional DSOs. A company can own both a regional DSO and local DSOs, but they must be managed as separate units. The three largest companies (Vattenfall, E.ON. and Ellevio) have more than 50 % of all customers connected to local DSOs and own more than 95 % of the regional systems in Sweden (in some countries referred to as sub-transmission systems).

B. Our role as the national regulatory authority (NRA)

Due to the lack of competition in the power system operation, regulation is required to promote efficiency, quality of supply and to ensure fair network tariffs for customers [7]. A network concession means a privilege with rights, but also with several obligations, which are governed by laws and regulations at different levels. The Swedish NRA, the Energy Markets Inspectorate (Ei), ensures that laws and regulations are followed, but also works continuously with evaluating the current legislations in order to adjust to changes in society and technology. The NRA should ensure that customers have access to a power system, to provide incentives for cost efficient operation with acceptable reliability and with objective, reasonable and non-discriminatory tariffs.

In 2003, the first performance-based regulation regarding allowed revenues was introduced, but later abandoned after legal processes and an EU requirement of practicing ex-ante. In 2012 a new revenue cap regulation was introduced, which since then has undergone major developments, both in 2016 [4] and in 2020. According to the Swedish Electricity Act, the transmission and distribution of electricity must be of good quality. More detailed rules on what is considered good quality is defined in secondary regulation published by Ei. It is the duty of Ei to monitor the compliance of those requirements, and to continuously evaluate if the current legal requirements are appropriate. The collection of CoS data is an important part of this work.

C. Continuity of supply data collection

The DSOs in Sweden annually report data for every customer in their power distribution system to Ei. The TSO is not subject to annual reporting obligation but provide aggregated outage data to Ei when needed for e.g. incentive schemes in the revenue cap regulation. The amount of outage data and other related information mandatory to submit has developed since the early 2000s:

- **2003-2009:** Aggregated CoS indicators (SADI/SAIFI for local DSOs and ENS/PNS for regional DSOs – see TABLE I.)
- **From 2010:** Detailed outage data and other information for each customer (including connection points to other grids). This includes data on customer category (SNI code – see TABLE I), annual energy consumption, fuse size, voltage level and a large amount of outage categories. The outage categories are defined to enable the distinction between notified and unnotified outages, and between outages caused by the DSO's own grid or not. It is also possible to divide the outages into some categories based on length. There is also information about the number of outages and the summarized outage length per each outage category. In total there are ~5.5 million power customers in Sweden, and with more than 20 different data parameters per customer, the amount of data collected by Ei sums up to more than 100 million data items.
- **From 2016:** Additional data per each customer is collected. The most significant new data are produced energy (before only consumed), maximum power (only for customers with tariffs based on actual power instead of fuse size) and information about municipality.

In addition to the data mentioned, Ei also collect other data from all DSOs each year, both economic and technical. This information is on a more aggregated level and are primarily used in the revenue cap regulation. Examples of such data are energy losses, length of different feeder categories and different expenditure categories. Furthermore, every four years we collect extra data needed for the revenue cap regulation including component information (age and category) at a detailed level.

D. Publications regarding continuity of supply in Sweden

Ei annually publishes a report on the CoS in Sweden. The report analyzes the most recent data collection from the DSOs and compares it with previous years. The report gives information to the public to highlight the importance of reliable power distribution and incentivize the DSOs by exposing their CoS outcome each year. Ei also publishes an extensive list of outcomes for several indicators per DSO and per municipality respectively on Ei's website [8] and at open data portals (Swedish https://oppnadata.se/ and European https://www.europeandataportal.eu). Furthermore, the data is used to create a map of Sweden showing different indicators per DSO, municipality and concession holder [9].

Swedenergy, the industry organization for companies that supply, distribute and sell energy in Sweden, also publishes CoS statistics each year based on facultative reports from the DSOs. Even though the reports are voluntary most customers are represented in the statistics. Contrary to the data collected by Ei this data includes the cause of the outage and the component which broke, while the data collected by Ei is based on each customers outage which is presented in this report [10]. Hence, the data from Swedenergy is a good complement and useful in reliability analyses where the data from Ei not is suitable. Additional information about the CoS in Sweden is found in a report from the council of European energy regulators (CEER https://www.ceer.eu/) which is a cooperation of independent energy regulators in Europe [11]. In the report Sweden's CoS and other information such as the regulation of CoS is compared with other European countries. The report was first published in 2001 and has since then been published in 2003, 2005, 2008, 2011 and 2016.

III. CoS in Sweden over two decades

A. Introduction

This chapter presents the outage indicators SAIDI, SAIFI, CEMI-4 and CEMI-12 (see TABLE I.) in Sweden over time. The indicators are calculated from unplanned outages longer than 3 minutes caused by faults in the local DSOs own grid, overlying or contiguous grid, if not otherwise stated.

B. SAIDI and SAIFI

Fig. 1 illustrates how SAIDI has varied between 2003 and 2018. The average annual outage time has been significantly higher in the years when major storms have occurred in Sweden, e.g. 2005 (Gudrun), 2007 (Per) and 2011 (Dagmar). After Gudrun in 2005 with severe consequences for the CoS, several new legislations regarding CoS has been implemented (see Chapter I). As a result, many DSOs have started to do investments in order to improve the CoS of their grids.

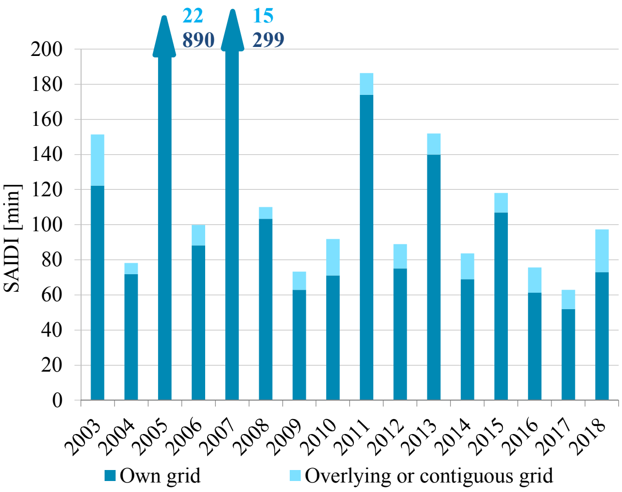

Fig. 1. SAIDI in Sweden between 2003 and 2018

Fig. 2 illustrates how SAIFI has varied between 2003 and 2018. SAIFI varies less between the years than SAIDI, which can be seen when comparing Fig. 2 and Fig. 1. The reason is that SAIDI is much more affected by single weather events than SAIFI. Consequently, the variation between years mostly depends on different CAIDI, see Fig. 3. It is also possible to conclude that outages due to faults in overlying or contiguous grids, on average, are shorter and varies less over time.

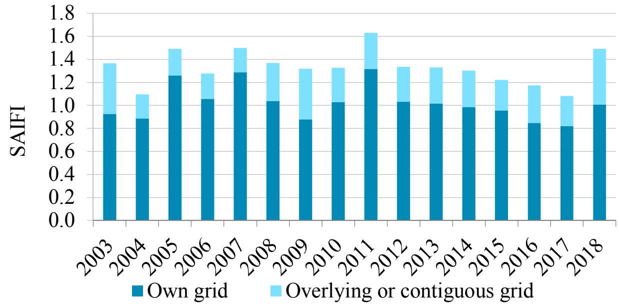

Fig. 2. SAIFI in Sweden between 2003 and 2018

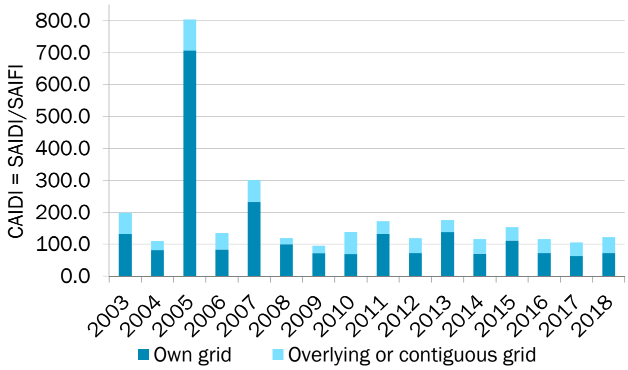

Fig. 3. CAIDI in Sweden between 2003 and 2018

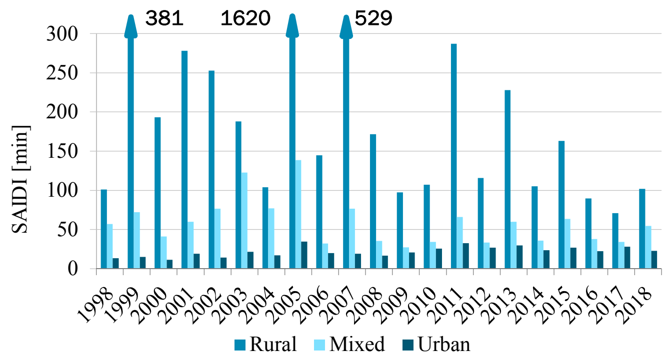

Fig. 4. SAIDI broken down by rural, mixed and urban grids from 1998

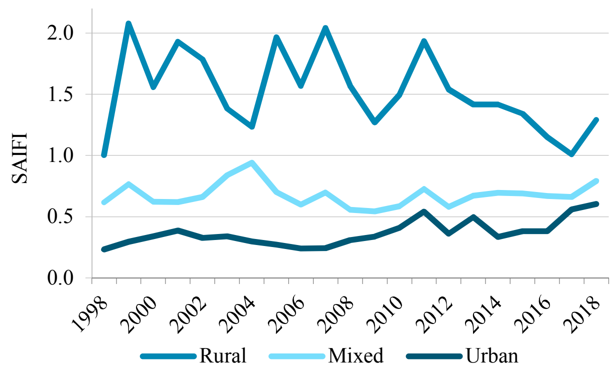

Fig. 5. SAIFI broken down by rural, mixed and urban grids from 1998

Fig. 4 and Fig. 5 shows SAIDI and SAIFI respectively caused by faults in the own grid since 1998, broken down by rural, mixed and urban grids (defined in TABLE I.). The outages in rural grids are both more frequent and longer than in grids with higher customer density. It is also evident due to Fig. 5 that severe storms affect the CoS to a greater extent in rural grid. There is generally a higher proportion of overhead lines (sometimes still uninsulated) in rural grids that makes the system more vulnerable for weather events. In addition, rural grids often lack redundancy, which means that failures lead to longer outages. Furthermore, longer distances often lead to longer time to detect a failure and to transport the repair team. However, there has been an increase of underground cables even in rural grids after 2005. There are also several other ways for DSOs to weatherproof power lines such as widen (or better clear) power lines corridors.

C. Other aspects on CoS

About half of the Swedish customers usually have at least one outage per year, a figure that normally doesn't vary so much over time. The share of customers with four or more outages per year (CEMI-4) has been around 10 % since 2010, while CEMI-12 is much lower but with a greater variation. The latter limit is never tolerated due to current minimum requirements defined by the NRA, while 4-11 outages can be individually evaluated whether it is considered as good quality or not from a legal perspective.

TABLE II. CEMI-4 AND CEMI-12 FOR 2010-2018 (IN BRACKETS, NUMBER OF CUSTOMERS WITH MORE THAN 3/11 OUTAGES RESPECIVELY)

	CEMI-4	CEMI-12
2010	10.1 % (538 899)	0.9 % (49 000)
2011	13.7 % (729 642)	1.4 % (72 059)
2012	9.5 % (506 074)	1.1 % (56 480)
2013	9.9 % (534 752)	0.7 % (39 339)
2014	10.1 % (543 361)	0.9 % (48 211)
2015	9.4 % (508 480)	0.7 % (36 287)
2016	8.5 % (464 066)	0.5 % (28 089)
2017	7.5 % (411 669)	0.2 % (10 294)
2018	10.1 % (556 677)	1.5 % (82 229)

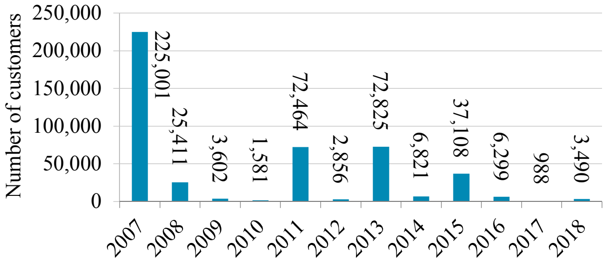

Fig. 6. Customers with one or more single outage >24 hours 2007-2018

Fig. 6 shows the number of customers affected by outages that lasted more than 24 hours during the period 2007–2018. Outages longer than 24 ours are not tolerated due to the Swedish Electricity Act since 2011. For outages that are against Swedish quality requirements (e.g. outages longer than 24 hours) the DSOs must send in cause, action and completion time of the action if requested by the NRA. The reason for this is to avoid such outages in the future.

According to the Electricity Act, a DSO may interrupt the transmission of electricity in order to take measures that are justified for electricity safety reasons or to maintain good operational and supply security. The outage must not go beyond what the measure requires, and the consumer must be notified in advance of the outage. Fig. 7 shows SAIDI regarding planned outages, presented separately as outages in own grid and overlying grids, between 2005 and 2018.

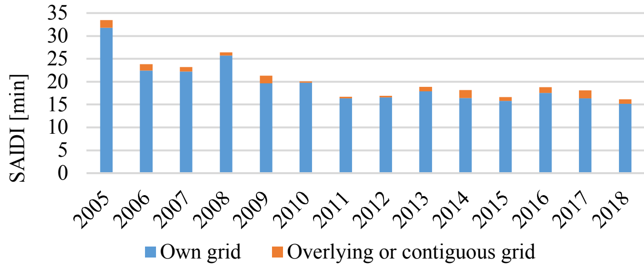

Fig. 7. SAIDI regarding planned outages 2005-2018

IV. CURRENT COS IN SWEDEN

A. Introduction

This chapter gives a detailed review of the CoS in Sweden exemplified by a single year (2018). For analyses of the CoS over time, see chapter III. Compared to previous years, the CoS relatively poor during 2018, especially considering that there were no severe storms. The increase was mostly due to single events resulting in outages in the overlying grids.

The statistics are calculated from unplanned outages longer than 3 minutes caused by faults in the local DSOs own grid, overlying or contiguous grid, if not otherwise stated.

B. National average – SAIDI and SAIFI

SAIDI was almost one hour and 40 minutes in 2018. Approximately 25 % of the outage time was caused by faults in the overlying or contiguous grids, which is notably high as the average over the last 15 years is about 12 %. The high share can partly be explained by many outages related to maintenance on the HVDC link between mainland Sweden and the island of Gotland. SAIFI was ~1.5 failures/customer, where 33 % was caused by the overlying or contiguous grids.

Two effective ways for DSOs to improve SAIDI and SAIFI is by vegetation management and the replacement of overhead lines with underground cables to protect the lines from weather events. The correlation between the share of underground cable and a low SAIDI was calculated to be -0.54 in 2018. Hence there is a clear relationship between a high share of underground cable and a low SAIDI.

C. National average – Other aspects on CoS

Around half of the customers in Sweden usually have at least one power outage per year. In 2018 the share of customers with power outages was higher than average. Fig. 8 shows the share of customers with at least x outages. Customers in Sweden had on average 1.5 outages in 2018. However, most customers had less outages than the average, which can be seen in Fig. 9. Approximately 3 % of customers had more than seven outages per year.

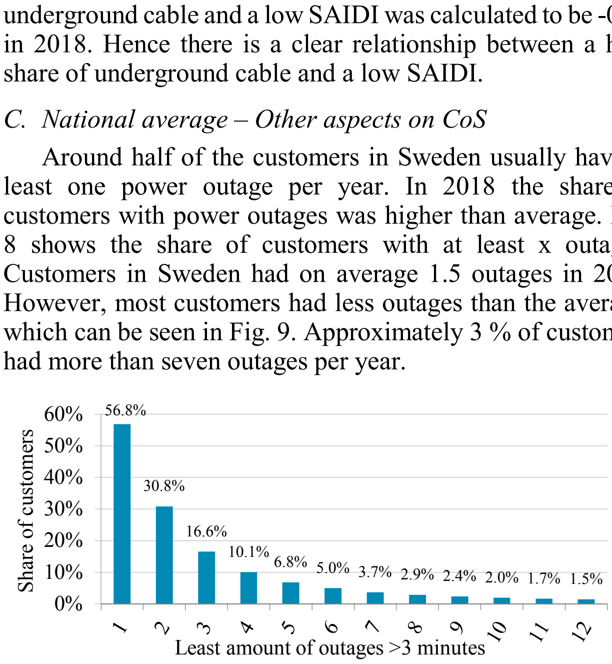

Fig. 8. Share of customers with x number of outages or more (CEMI-X)

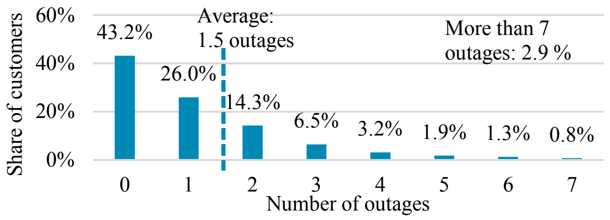

Fig. 9. The distribution of outages for individual customers.

According to minimum requirements defined by the Swedish NRA, it is good quality (regarding frequency) if a low voltage customer has less than four outages per year, which was the case for around 90 % of the customers in 2018. Around 1.5 % of the customers had more than eleven outages in 2018 which is always classified as having poor quality. According to Swedish Electricity Act DSOs should ensure that customers do not have an outage lasting longer than 24 hours, which was the case for 0.06 % of the customers in 2018. Around 0.7 % of the customers in 2018 had a combined outage time of 24 hours, that being the sum of all their outages.

D. Broken down by municipality/region

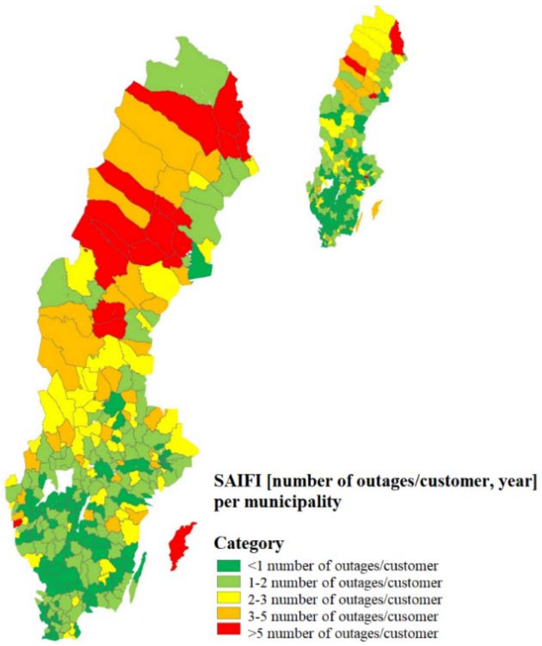

Fig. 10. SAIFI per municipality during 2018 (2017 in the miniature map)

Fig. 10 shows the variation of SAIFI between Swedish municipalities in 2018. The northern parts of Sweden (that in average has low customer density) and the island Gotland had, in average, the highest SAIFI. Most municipalities (262 out of 290) had a SAIFI below four. The capital of Sweden, Stockholm, had a SAIFI equal to 0.4.

Fig. 11 shows the variation of SAIDI between Swedish municipalities in 2018. The southern parts of Sweden had on average shorter outages than in the northern parts. The correlation between the customer density and SAIDI was -0.32 in 2018. This means that more densely populate areas tend to have lower SAIDI. The southern parts of Sweden are in average more densely populated than the northern parts.

Almost a third of all municipalities had a shorter average outage time than one hour in 2018. About 11 % of the municipalities had a lower SAIDI than Stockholm whose SAIDI was equal to 0.5 hours. There is however a big difference between the municipalities. The highest SAIDI of a municipality was 18,9, while ~11 % had over five hours.

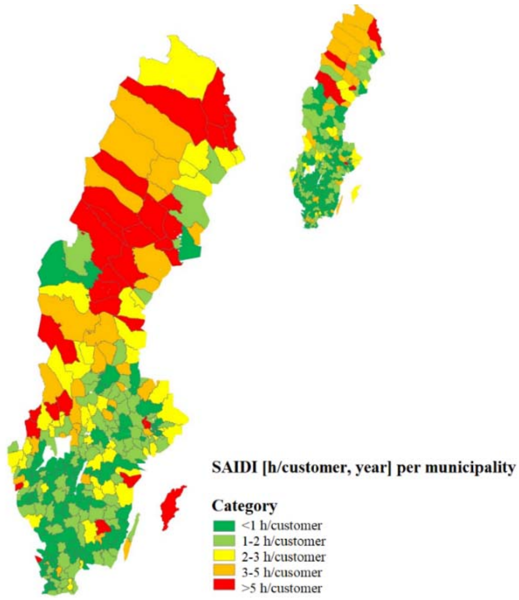

Fig. 11. SAIDI per municipality during 2018 (2017 in the miniature map)

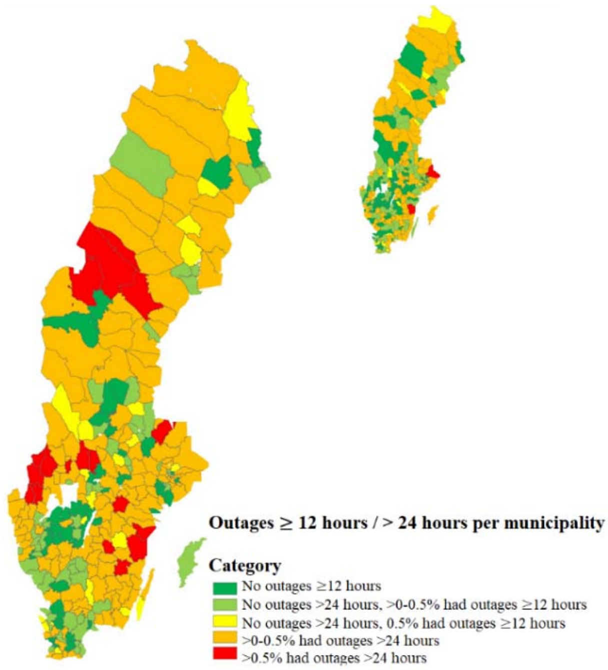

Fig. 12. Statistics of very long outages per munnicipality 2018 (2017)

Fig. 12 show statistics of outages longer than 12 and 24 hours respectively (important limits due to current legislation, see chapter I) divided by municipalities. Around 57 % of all municipalities had at least one outage longer than 24 hours (orange or red in the map) and 22 % did not have any outage longer than 12 hours (dark green in the map).

E. Broken down by customer categories

There are several possible ways to divide customers into different categories based on our collected data; for example, based on voltage levels or the customer code the DSO must enter for each customer. All households have the same code, but other kind of customers are divided into hundreds of categories by SNI codes (defined in TABLE I.). However, all those categories are aggregated into five overall customer categories (plus border points as an own category) that are used in an incentive scheme in the revenue cap regulation. Those five or six categories have different cost parameters based on willingness to pay, which is summarized in [7].

TABLE III. provide statistics divided by the customer categories used in the revenue cap regulation. More than 85 % of all customers are households, but they only account for <30 % of the energy consumption. Commercial services have on average the best CoS which is logical since they often are situated in urban areas. The fact that the category Agriculture has the lowest CoS on average is also logical since they are often situated in rural areas. Farms therefore often have access to own backup generation if the power supply is critical, especially farms with animal husbandry.

TABLE III. AGGREGATED PER CUSTOMER CATEGORY

Customer category	Number of customers	Energy [TWh]	SAIFI	SAIDI
Agriculture	39 843	1.65	3.12	235.92
Industry	108 415	48.33	1.45	109.49
Commercial service	489 791	30.43	1.27	80.68
Public service	141 616	7.54	1.51	99.71
Household	4 745 043	36.34	1.66	116.30
All	5 524 708	124	1.63	113.45

V. OTHER STATISTICS OF INTEREST BASED ON THE DSO'S S ANNUAL OUTAGE REPORTING

Although the primary purpose of collecting this data is to monitor CoS, it could be used for other kinds of statistics as a positive side effect. The results provided in Fig. 13 give an example of another kind of analysis possible. There is a tendency of rapidly increased amount, but from low levels, of so-called prosumers (such as households with installed PV) between 2016 and 2018. For households the share was 0.14 % in 2016, 0.21 % in 2017 and 0.38 % in 2018.

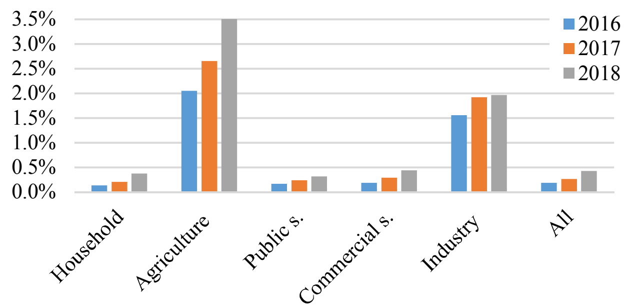

Fig. 13. Share of low voltage customers, divaded by category, that at least one time during a year exported surplus of produced electric energy

Another possible usage of the collected data is the amount of energy consumed aggregated to different customer categories or geographic areas.

VI. CLOSURE

The aim of this paper is to publish statistics based on the considerable amount of data collected from all Swedish DSOs during a relative long period of time, but also to share our thoughts as an NRA on the increasing legal focus on CoS since the early 2000s. Both tendencies over time and more detailed analyzes regarding 2018 (the latest year with available quality assured data) are presented and analyzed.

As a result of stricter rules on power outages, there have been major investments in more reliable power distribution systems over the past decade. This can be assumed to have resulted in the positive tendency of the CoS even if the CoS vary both up and down. The results shown in this paper indicate that tendency, but more analyses are needed for more accurate conclusions. Years with mild weather are slightly better and years with severe storms are less negative for the CoS, even if it is still far from good enough.

The significant variation of CoS over time can essentially be explained by the amount of severe weather events. It is especially the length of unplanned outages and indicators that measures unaccepted quality due to Swedish legislation (outages >24 hours and customers with >11 outages) that significantly vary, while the share without any outages at all, SAIFI and planned outages are more constant over time. Urban areas have on average better CoS than rural areas. This can be explained with the fact that rural areas have more overhead lines and longer time to detect a failure and to transport the repair team in average due to longer distances.

We believe that the experiences from Sweden may be of value for others when developing laws and regulations in the future. This paper also contributes by informing about available data (also from others than Ei) related to Swedish power outages for others to use when e.g. comparing countries or developing probabilistic models. The data also covers other statistics than power outages, where we provide an example by showing the increased share of prosumers the last years.

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