THE VALUE OF LOST LOAD IN SWEDISH INDUSTRY

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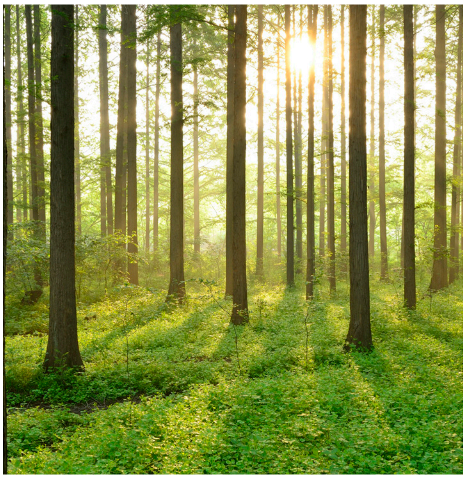

EFORIS
ELMARKNADENS FUNKTION
OCH ROLL I SAMHÄLLET

Energiforsk

The value of lost load in Swedish industry

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Foreword

EFORIS, Elmarknadens funktion och roll i samhället, is a research program regarding electricity market design. The program was initiated by Energiforsk and involves dozens of highly reputable Swedish and international researchers. The author/authors are responsible for the content.

Summary

The power system is undergoing a drastic transition towards a system with high degree of intermittency at the same time as the transition in other sectors will require more electricity. Taken together this will make it more challenging to keep the instantaneous balance between demand and supply in the power market with increasing risks of interruptions and power outages as a result. The objective of this study is to estimate the cost of power outages in the Swedish industrial sector by using firm-level, production data. Our estimates of interruption costs are based on firms' actual behavior concerning their use of electricity and the values created. The main approach is complemented with a qualitative study based on a questionnaire targeting key-persons in a small number of industrial production facilities. The purpose with this is to identify firm or facility specific aspects that that are not revealed by annual firm level data.

The main conclusion from this study is that the costs for the industry of supply interruptions are considerable, and seems to have increased over time, suggesting that the industrial sector has become more vulnerable to supply disturbances. In 2016 the estimated cost of a one-hour outage for an average industrial facility in Sweden was approximately 23 times larger than the value of the electricity not delivered (SEK 9502 versus SEK 400), whereas the cost in 2004 was approximately 13 times the market value of the electricity not delivered. However, there is substantial variation across firms and sectors. For an average facility in the electro and motor vehicle industry, for example, a one-hour cost is, according to our estimates, about 120 and 105 times the market value of the electricity not delivered, respectively (SEK 43680 versus SEK 415 for an average motor vehicle firm). In the pulp and paper industry, on the other hand, the outage cost is only about 5 times the value of undelivered electricity in spite of a relatively high outage cost in absolute value (SEK 27730). The reason for the relative low ratio for the pulp and paper industry is the very high level of electricity intensity.

The estimated costs should however be interpreted with care since they are based on the assumption that the interruption in production processes corresponds exactly to the duration of the outage, but also that the production losses during the outage are lost forever and cannot be compensated for in any way. Importantly, according to the results from our survey most firms or production facilities reported that the production interruption becomes noticeable longer than the power outage itself. In addition, most of them reported additional costs because of an outage, such as costs for overtime and delivery delays. On the other hand, several facilities firms reported that they may be able to “take back” the production losses during a year. Altogether, the first effects seem to dominate according to the survey results and the cost estimates reported should therefore be interpreted as lower bounds.

Keywords

Value of lost load, black-out, revealed preferences, Swedish industry, outage cost

Avbrottskostnader, produktionsfunktionsansats, svensk industry

Sammanfattning

Elsystemet och kraftmarknaden genomgår en drastisk övergång till ett system med hög intermittens samtidigt som omställningen i andra sektorer kräver mer el. Dessa trender gör det mer utmanande att matcha efterfrågan och utbud på kraftmarknaden. Om balans mellan efterfrågan och utbud inte säkerställs kommer hushåll och företag sannolikt att drabbas av fler avbrott i strömförsörjningen. Syftet med denna studie är att uppskatta kostnaden för strömavbrott i den svenska industrisektorn med hjälp av produktionsdata på anläggningsnivå. Vi baserar våra uppskattningar av kostnader för avbrott på produktionsanläggningarnas faktiska beteende avseende deras användning av el och de värden som denna användning skapar. Vår huvudansats kompletteras med en kvalitativ enkätstudie riktad mot nyckelpersoner i ett litet antal industrianläggningar. Syftet är att identifiera anläggningsspecifika aspekter som inte fångas av årliga uppgifter på företagsnivå.

Den huvudsakliga slutsatsen från studien är att kostnaderna för leveransavbrott i industrisektorn är betydande och verkar ha ökat med tiden, vilket eventuellt tyder på ökad sårbarhet för störningar i eltillförsel. År 2016 var den beräknade kostnaden för en timmes avbrott för en genomsnittlig industrianläggning i Sverige cirka 23 gånger större än värdet på den el som inte levererades (9502 SEK mot 400 SEK), medan kostnaden år 2004 var cirka 13 gånger förlorat marknadsvärde på el. Det finns dock mycket stor variation mellan företag och sektorer. För en genomsnittlig anläggning inom elektronik- och motorfordonsindustrin är till exempel kostnaden för en timmes avbrott cirka 120 respektive 105 gånger marknadsvärdet för den el som inte levererats (43680 SEK mot 415 SEK för en genomsnittliga motorfordonsföretaget). Inom massa- och pappersindustrin är avbrottskostnaden bara cirka 5 gånger värdet av icke levererad el trots en relativt hög avbrottskostnad i absolut värde (27730 SEK). Anledningen till det relativt låga förhållandet för massa- och pappersindustrin är den mycket höga elintensiteten i sektorn.

Det bör betonas att dessa siffror ska tolkas med försiktighet eftersom de är baserade på antagandet att avbrottet i produktionsprocesserna motsvarar exakt avbrottets varaktighet, men också att produktionsförlusterna under avbrottet förloras för alltid och inte kan kompenseras på något sätt. Enligt resultaten från vår enkätundersökning rapporterade dock en majoritet av anläggningarna att produktionsavbrottet märks längre än själva strömavbrottet. Dessutom rapporterade de flesta ytterligare kostnader på grund av ett avbrott, till exempel kostnader för övertid och leveransförseningar. Å andra sidan rapporterade flera anläggningar att de kanske kunde "ta tillbaka" produktionsförlusterna under loppet av ett år. Sammantaget verkar dock de första effekterna dominera enligt våra resultat. De kostnadsberäkningar som redovisas ovan bör därför tolkas som lägre gränser.

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1 Introduction

On the national and European level, there is currently a lively discussion about how to secure a high level of reliability of power supply in the future. The discussion has emerged for (at least) three reasons. First, after the de-regulation of the power market in 1996, Sweden has not had an explicit policy target concerning the reliability of power supply. The reliability of power supply is essentially up to the market and its actors supplemented by a procured reserve capacity. The operation of the reserve capacity has been guided by the market price on Nord Pool in the cold season, and as such, the reserve is targeting shortages of generation capacity rather than reliability problems related to intermittency or operation and maintenance of the power grid. The operation of the reserve capacity will change in the future due to EU regulations that will necessitate an explicit reliability norm. Second, ambitious climate targets have been introduced on the national and EU level that require a phase-out of fossil fuels in the power sector. These targets also encourage substitution of fossil fuels for electricity in the transport and industrial sectors, putting additional stress on the power system. Third, ambitious renewable energy targets have been introduced on the national and EU level that require a phase-out of nuclear power. All together, these factors imply that the power system is undergoing a drastic transition towards a system featuring a high degree of intermittency at the same time as the transition in other sectors will require that more electricity must be produced. These trends will make it more challenging to keep the instantaneous balance between demand and supply in the power market. If that balance is not secured, households and firms will most likely suffer from more interruptions in their use of power due to power outages (brown-outs and black-outs).

It should be acknowledged that it is costly, if even possible, to create a power system that guarantees power delivery under all circumstances. To determine how much resources should be put into securing the reliability of power supply it is necessary to investigate how much a reliable delivery of electrical power is worth to the society. That value is reflected in the total willingness to pay (WTP), among households, firms, and public actors, for keeping the currently high level of reliability (or enhance it further), or put differently, their WTP for avoiding a higher frequency of power outages. Several measures can be implemented to secure or enhance the reliability level, such as investments in new transmission and distribution capacity, replacement of old capacity, weather protection of power lines, provision of balancing and reserve generation capacity, and/or provision of demand flexibility. When we know the costs and benefits associated with such measures, a benefit-cost analysis framework can be applied to determine whether they are justified from a societal perspective. Therefore, reliable estimates of the WTP for avoiding power outages are of central importance for establishing the optimal reliability level.

It exists a large body of literature that use a variety of methods to estimate the cost of power outages for different sectors and countries. The most popular estimation method is based on stated preferences where representatives for households and/or firms are asked to state their WTP for avoiding one or more power outages in a hypothetical scenario. The stated preferences approach is appealing since it measures the theoretically correct value and can be applied in all circumstances and is flexible to handle all types of scenarios concerning duration, time of day, year, etc. One major caveat with the approach is that respondents may not state, or know, their true WTP since their answers have no real-life consequences or if the valuation task for other reasons is not incentive compatible (Carson and Groves, 2007). These problems give rise to hypothetical and strategical biases in the WTP estimates. A summary of the previous literature that compare economic behavior in hypothetical and real market situations (revealed preferences), finds that the hypothetical bias on average warrants division by a correction factor of three, i.e., on average stated preferences approaches overestimates the WTP with 300 percent (Loomis, 2011). Thus, it is important to keep in mind that stated preferences may give incorrect estimates of theoretically correct values.

In Sweden, all estimates of outage costs are based on stated preferences where the data has been collected either by mail surveys or by telephone interviews (Andersson and Taylor, 1986; Svenska Elverksföreningen, 1994; Carlsson and Martinsson, 2006, Carlsson and Martinsson, 2007, Carlsson and Martinsson, 2008; Carlsson, et al., 2019). The objective of the present study is to complement the previous literature by estimating the cost of power outages in the Swedish industrial sector by using firm-level, production data. This means that we base our estimates of costs of interruptions on firms' actual behavior concerning their use of electricity and the values that this use creates. The study can be described as routed in revealed preferences measured on an aggregated level (annual firm level) and is similar to the one outlined in De Nooij et.al (2007) and Leahy and Tol (2011), commonly known as the production function approach. The paper contributes to the previous studies by including a problematization of the fact that the method may not properly capture site specific and firm specific characteristics, and as such do not measure theoretically correct values. For that reason, our main approach is complemented with a qualitative study, where we use a questionnaire targeting key-persons in a small number of industrial companies. The purpose with the survey study is to identify firm-specific aspects that that are not revealed by annual firm level data, to get a more qualitative picture of how firms perceive the consequences of power outages, and how that aligns with the microeconomic production data approach.

The remaining of the report is structured as follows. In Section 2, we provide a more in-depth background as to why we want to estimate the value of lost load. Section 3 provides a basic conceptual framework of how to measure costs of load restrictions and outages, whereas a review of the empirical literature is given in Section 4. In Section 5, we report results concerning the value of lost load using firm level data. In Section 6, we present results from our qualitative study. Finally, Section 7 contains a discussion of the results and how the results should be used in practice, whereas considering different scenarios for the future development of the power market.

2 Background

As above-mentioned, the whole society is undergoing a major transformation that may cause considerable stress on the power system, not the least due to the foreseen increase in electricity demand as a result of the electrification of transports and industries. One possible consequence is less reliable electricity supply and increased risk for outages. In this report we set out to estimate the cost of power outages in the industrial sector in order to inform policy makers and other stakeholders about the value for society of securing a reliable supply of electrical power. Below we review three important driving forces to why reliability issues are currently debated and bring them together in a general discussion under the transition umbrella.

2.1 RELIABILITY TARGETS

European power markets have already undergone a transition during the two last decades due to de-regulation. Markets have been opened for production and sale of electricity and thereby changing the conditions for producers, retailers, and consumers in a fundamental way. Perhaps the most obvious change for consumers in Sweden is that they can now choose freely from a large number of electricity suppliers who offer them a multitude of different contracts. However, this freedom and responsibility does not cover the reliability of supply but rather concerns affordability. As above-mentioned, the Swedish transmission system operator (Svenska Kraftnät, SvK) procures an operating reserve with the aim to secure enough power generation capacity in wintertime. The plans for the operating reserve have changed over time and the previous plan of the Swedish government to phase out the reserve capacity gradually by 2020 has changed to transforming the operating reserve to a strategic reserve guided by a reliability norm. The Energy market inspectorate is currently working on developing the norm.

Prior to the de-regulation of the Swedish power market in 1996 an explicit reliability target for power supply was in place. The target was set both in terms of risk for energy- and power shortage. The target for energy shortage was that the risk of energy shortage must not exceed three percent, and that the risk of power shortage must not exceed 0.1 percent. This can be described as that energy shortage was not allowed to occur more than once in about 30 years, and that power shortage was not allowed to occur more than nine hours per year (one thousandth of the time).[1]

2.2 CLIMATE AND RENEWABLE ENERGY TARGETS

Sweden has for a long time worked seriously on reducing GHG emissions and developing climate policies. A carbon tax was introduced already in 1991, and ambitious targets was introduced for CO_2 emission levels in 2010 and 2020. Today, the long run target is to accomplish net-zero emissions and 85 percent reduction of the GHG emissions from Swedish territory by 2045. Furthermore, the CO_2

[1] SvK (2015).

emissions from domestic transports should decrease with 70 percent during the period 2010-2030. These targets imply that some industrial sectors and the transport sector must transform fundamentally. For the transport sector, projections show that a rapid uptake of electrical vehicles will result in a 5 TWh increase of the sectors electricity demand. In the industrial sector the electricity demand is expected to increase with about 20-25 TWh by 2030 (IVA, 2016; Sweco, 2020). In a 2045-perspective, the increase of electricity demand will be much higher where the production of steel and iron will demand around 70 TWh more than they currently do (IVA, 2019, Sweco, 2020; LKAB, 2020).

The climate policy in Sweden reflects the ambitions of the EU which are to accomplish net-zero emissions by 2050. Recently, it was decided that the ambitions for 2030 shall be increased from a reduction of at least 40 percent to at least 55 percent in greenhouse gas emissions (from 1990 levels). The impact assessment underlying the decision show that the share of renewables in the electricity mix must increase from around 32 percent to at least 65 percent by 2030. Thus, the trends in Sweden with increasing intermittence in the power production is shared with the EU as a whole. Overall, this means a substantial change in the structure of energy use, in the sense that the use of fossil fuels has to be phased out in all sectors, increasing demand for (fossil free) electricity substantially.[2]

Both Sweden and the EU complement the climate target with targets for the share of renewable energy. This means that there are constraints on how the climate target is supposed to be reached. In the EU, the target is that the share of renewables should reach 32 percent by 2030, but due to the new climate target the target will be adjusted. In Sweden, the target is to reach a 100 percent renewable power production by 2040 (Prop. 2017/18:228). Among other things, this logically means that nuclear power has to be phased out and replaced by renewable sources like wind, solar, and bioenergy. However, the target neither explicitly prohibit investments in nuclear power nor does it imply that nuclear will be phased-out by explicit political decisions. In practice however, the target is a statement that the government will facilitate massive investments in wind and solar power, which indirectly may affect the business case for nuclear power. An apparent consequence is an increase in a more weather-dependent and intermittent power supply.

2.3 THE TRANSITION TOWARDS SUSTAINABLE ECONOMIES

The power system is undergoing a drastic transition towards a system featuring a high share of production from renewable energy sources. The energy production will mainly come from weather-dependent technologies such as wind turbines and photovoltaic solar panels, implying a risk that the reliability will deteriorate due to more intermittency. Altogether, the above-mentioned factors imply that more electricity will be generated by capacity that currently does not exist and that will make it more challenging to keep the instantaneous balance between demand and supply in the power market. Apart from a higher risk of disturbances we should

[2] A substitution from fossil fuels to electricity would increase the use of electricity in Sweden by approximately 50% (IVA, 2019).

expect an increase in price volatility, both intraday, within weeks, and between seasons.

Because of the transformation of the supply side globally, there is an ongoing discussion of whether energy-only markets, which currently are the most common market design, have to be complemented with some kind of capacity mechanism to ensure generation capacity in peak periods (Joskow, 2008a, 2008b, Newbery, 2016). Related to this is also the discussion of demand management and demand flexibility, which in turn is closely related to the discussion of incentive mechanisms facing companies and households (see Broberg and Persson, 2016, Broberg et al. 2017, Broberg et al. 2021). Many types of measures can be implemented to secure a high reliability of power supply and it is important that the overall policy design is cost effective, i.e., stimulates implementation of the measures that minimizes the social cost of reaching an acceptable reliance level. In order to determine an acceptable reliance level, it is necessary to empirically investigate the value of lost load.

3 The value of lost load: a conceptual framework

To accurately measure the cost of power outages it needs to be specified what actually is to be measured and how it is done. Basically, we want to measure cost of supply disturbances and electricity outages in terms of lost utility for households and lost profits for firms following interruptions in their preferred consumption and/or production activities. The outage cost will differ between different consumers and firms and depend on: (1) substitution possibilities (between inputs and between time periods); (2) duration of the interruption; (3) when the interruption occurs (season, weekday, and time of the day); (4) if stored inputs and outputs will be negatively affected; (5) if precautionary measures are taken (e.g., backup facilities); and (6) the prices of the service/product that are produced.

Concerning substitution possibilities, it may be for some firms that a continuous flow of electricity is essential, whereas for other firms, electricity can be replaced quickly either by some other energy source or even by labor. It can also be the case that firms at a reasonable cost can move their production from one point in time to another. Furthermore, the substitution possibilities may differ between seasons, or between different times of the day, e.g., it may be easier to cope with an outage occurring at the end of the day or at the end of the week.

Below we outline conceptually how interruption costs can be measured and calculated, given different assumptions concerning substitution possibilities and input flexibility. The purpose is: (1) to illustrate that outage cost estimates can differ substantially depending on what assumptions are made concerning input flexibility; and (2) to serve as benchmarks for the empirical estimations later in the report. It should be stressed that many factors that will affect outage costs are not considered, such as time of day, time of year, and duration.

Suppose a firm that produces a product that can be sold at a given market price P (or many products given a price vector). As inputs, the firm uses the variable inputs electricity (E), labor (L), material (M), and a capital stock (K) that cannot be changed in the short-run. The flexible inputs can be bought at given market prices. A firm's (restricted) profit is then:

$$\pi^0 = Pf(E^0, L^0, M^0; K^0) - w_E E^0 - w_L L^0 - w_M M^0 - F , \qquad (1)$$

where E^0, L^0, and M^0 are profit maximizing quantities of electricity, labor, and material with corresponding prices w_E, w_L, w_M, and F is the fixed capital cost. The superscript "0" denotes initial quantities and profits.

Assume that a power outage occurs ($E = 0$), the profit then becomes:

$$\pi^1 = Pf(0, L^1, M^1; K) - w_E 0 - w_L L^1 - w_M M^1 - F , \qquad (2)$$

where superscript "1" denotes quantities and profits when there is an outage. Obviously, the difference in profit will depend on the production technology given by *f(.)*, which decides to what extent the use of labor, material (capital assumed fixed) can be adjusted as a response to the outage. In general, the change in profit resulting from a black-out is:

$$\begin{aligned}\Delta\pi &= \pi^1 - \pi^0 = (Pf(0, L^1, M^1; K) - w_L L^1 - w_M M^1 - F \\ &\quad -(Pf(E^0, L^0, M^0; K) - w_E E^0 - w_L L^0 - w_M M^0 - F) \\ &= P\Delta f - w_L \Delta L - w_M \Delta M + w_E E^0\end{aligned} \tag{3}$$

That is, the change in profit equals the change in revenue plus the change in variable cost. From this, it is obvious that the magnitude of the loss depends on the technology (substitutability), and how flexible labor and material inputs are. If labor and material are good substitutes for electricity, i.e., electricity is non-essential, and both labor and material are flexible inputs, then the loss is relatively low, while the loss is relatively high if labor and material cannot replace electricity, or is a bad substitute, and labor and material is non-flexible. [3]

Lower limits on the lost value (both labor and material are completely flexible) can be found directly from (3). If electricity is a necessity in production, then a lower limit on the lost value is:[4]

$$\begin{aligned}\Delta\pi^L &= \pi^1 - \pi^0 = 0 - 0 - 0 - 0 - F - (Pf(E^0, L^0, M^0; K) - w_E E^0 - w_L L^0 - w_M M^0 - F) \\ &= -(\pi^0 + F)\end{aligned} \tag{4}$$

i.e., the lost profit and the fixed cost.

An upper limit of the loss is when production ceases completely as a result of the black-out (again, we assume electricity is a necessary input), the labor force becomes completely unproductive and cannot be dismissed, and material cannot be stored and therefore get spoiled. Given this, profit becomes:

$$\pi^1 = P \cdot 0 - w_E 0 - w_L L^0 - w_M M^0 - F \tag{5}$$

The change in profit is then:

$$\begin{aligned}\Delta\pi^U &= \pi^1 - \pi^0 = -w_L L^0 - w_M M^0 - F - (Pf(E^0, L^0, M^0; K) \\ &\quad - w_E E^0 - w_L L^0 - w_M M^0 - F) \\ &= -(Pf(E^0, L^0, M^0; K) - w_E E^0) \\ &= -(\pi^0 + w_L L^0 + w_M M^0 + F) = -(VA + w_M M^0)\end{aligned} \tag{6}$$

The value lost as a result of the outage, given that labor (and capital) cannot be adjusted, and that material get spoiled equals the value added (profit plus labor and capital cost) plus the value of spoiled material. This can be considered as an upper limit for the economic values that are lost due to the lost load. This upper limit is relevant for outages with relative short durations, but long enough for material to get spoiled. For a dairy firm, for example, material input may be

[3] By inflexible material we here mean that the firm have material that will be spoiled if production is reduced, it cannot be stored to be used after the outage (e.g., certain food production).

[4] An even lower lost will of course occur if electricity is non-essential and labor and material is flexible. In that case the firm will adjust its production in a profit maximizing way, which not necessarily implies zero production.

spoiled relatively quickly, whereas for a sawmill material can be stored for a longer time. So, for most manufacturing firms, material being spoiled during a shorter black-out is not a serious issue to account for.

If material that are not used during the outage have an alternative value, e.g., in another point in time through storage, the economic value lost due to a black-out can be written as:

$$\begin{aligned}\Delta\pi^{I} &= \pi^{1}-\pi^{0} = -w_{L}L^{0}-w_{M}0-F-(Pf(E^{0},L^{0},M^{0};K)-w_{E}E^{0}-w_{L}L^{0}-w_{M}M^{0}-F)\\ &= -(Pf(E^{0},L^{0},M^{0};K)-w_{E}E^{0}-w_{M}M^{0}) \qquad (7)\\ &= -(\pi^{0}+w_{L}L^{0}+F) = -VA\end{aligned}$$

That is, the loss equals the loss in the value added by the firm.

Above we have used a simple (production economic) framework to describe a firm's economic loss from a black-out. The description is based on several simplifying assumptions. One being that the firm operates in a perfect competitive setting, which means that it cannot reduce the loss by, say, hiring more labor to produce more after the outage.

Another way to describe the values lost is to model the profit as a function of the electricity price. If, as above, labor and capital are fixed inputs we can write the profit function as:[5]

$$\begin{aligned}\pi(P,w_{E},w_{M};L,K) &= Pf(E(P,w_{E},w_{M};L,K),M(P,w_{E},w_{M};L,K);L,K)\\ &\quad -w_{E}E(P,w_{E},w_{M};L,K)-w_{M}M(P,w_{E},w_{M};L,K)-w_{L}L-F \qquad (8)\end{aligned}$$

Suppose that there exists a choke price of electricity, $\overline{w}_E$, for which demand for electricity equals zero. The change in profit is then:

$$\Delta\pi = \pi(P,\overline{w}_{E},w_{M};L^{0},K)-\pi(P,w_{E}^{0},w_{M};L^{0},K) = \int_{w_{E}^{0}}^{\overline{w}_{E}} \frac{\partial\pi(P,w_{E},w_{M};L^{0},K)}{\partial w_{E}} dw_{E}, \quad (9)$$

which is the area under the electricity demand curve, which equals the loss in (7) for the case when electricity is a necessary input and materials does not spoil.

As mentioned above this loss may be relevant for outages with relative short durations, such as minutes or maybe a couple of hours. For longer durations, though, it is reasonable to believe that part of the labor force can be used for maintenance and other activities that may have a value for the firm, or even laid off. A lower limit of the loss can therefore be written as:

$$\Delta\pi = \pi(P,\overline{w}_{E},w_{L}^{0},w_{M};K)-\pi(P,w_{E}^{0},w_{L},w_{M};K) = \int_{w_{E}^{0}}^{\overline{w}_{E}} \frac{\partial\pi(P,w_{E},w_{L}^{0},w_{M};K)}{\partial w_{E}} dw_{E} \quad (10)$$

In summary, the upper limit loss from a supply interruption, or outage, equals the value added or the area under the restricted demand curve (equation (9)), whereas the lower limit equals the area under the unrestricted electricity demand curve, i.e.,

[5] Here it is assumed that that material input is flexible.

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the demand curve that allow for adjustments in labor and material (equation (10)). From (9) and (10) it should also be clear that the value of the lost load could be estimated, given that we know what the demand function for electricity looks like. An illustration is given in figure 3.1.

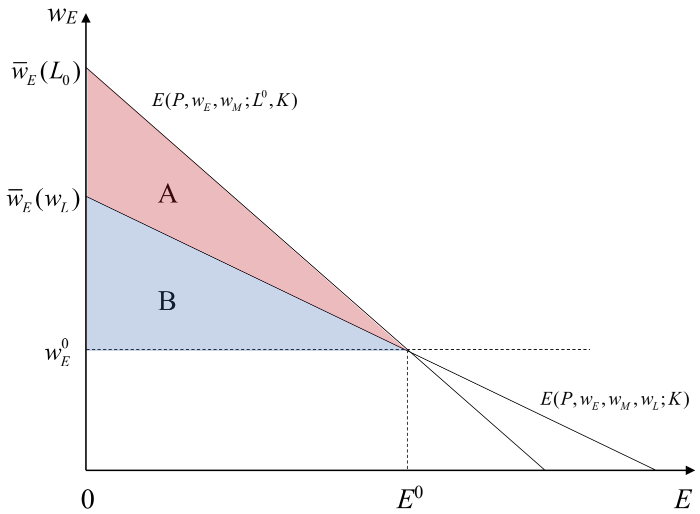

Figure 3.1. Outage cost.

The flatter demand curve in figure 3.1 illustrates demand for electricity when capital is a fixed input, but labor is flexible, whereas the steeper one illustrates the case when also labor is fixed (or have no alternative value). The cost of an outage in the case when labor is flexible is then area B, the blue area. This corresponds the loss in profit according to equation (4). If labor is fixed, the cost of an outage will be the area under the restricted demand function, the red and blue areas (A+B), which corresponds to the value added according to equation (7).

The partial equilibrium framework above assumes that an outage does not affect equilibrium prices on outputs or inputs. This is of course a questionable assumption, especially for outages with long duration that affects large areas. However, for short durations and geographically limited outages it may be reasonable to assume that prices are unaffected. Furthermore, different firms/sectors are often economically and technologically intertwined in the sense that output from one firm/sector is used as an input in other firms/sectors. An outage in a specific firm/sector where electricity is a necessity may therefore cause production losses in other firms/sectors, even if they are less dependent on electricity. To account for that, a general equilibrium or input-output model is needed that keep track of, and considers, all the interlinkages in the economy.

In most empirical studies on the value of lost load for firms and sectors the basis for estimation is equation (7), i.e., the value added (see de Nooij et al., 2007, Leahy and Tol, 2011). These estimations assume that electricity is a necessary input, that labor input is fixed, and that material input is completely flexible. These assumptions may be reasonable for some industries, but do not hold for all industrial activities. In the empirical estimations in section 4 we will utilize the results above to estimate the value loss under different assumptions concerning production technology and input flexibility, and hence get estimates on upper and lower limits of the loss.

In the derivations above it is (implicitly) assumed that the optimal quantities of inputs used (electricity, labor, material), and hence output, is decided without taking into account uncertainties involved, both with respect to whether an outage will occur and to its duration. Considering that uncertainty is a reality, perhaps a more relevant way to approach the issue is like Tishler (1993), where the firm initially maximizes its profit by selecting the amount of electricity and labor, conditional on its belief concerning electricity reliability. Suppose for example that the firm is certain about a black-out already at the beginning of, say, the day, and that it will continue the whole day. Then, given no hired labor and material in stock that is spoiled, the loss will be equal to the loss in profit, as described in equation (4) above. However, if there is uncertainty about whether a black-out will occur or not, and how long it will last, this has to be considered when deciding how much labor to hire and how much electricity to be used prior to an eventual black-out. At the end, this means that the expected cost of a black-out will depend also on the probability distribution for a black-out to occur and its duration.

An additional way to illustrate the loss caused by an outage, related to the approach in Tishler (1993), is in terms of cost for hedging/insuring against an undesirable outcome, like an outage. Being faced with the uncertainty of a potential outage will give an incentive to hedge against undesirable outcomes. This hedge cost, or foregone profit, will then depend on the optimal level of electricity usage in case of no outage risk, the perceived risk of an outage, and the risk preferences. This can be related to what is commonly referred to as certainty equivalence; a concept that considers a situation where the firm is faced with a risk of a bad occurrence. In relation to VoLL, that would be the risk of a supply interruption and what the firm is willing to pay to get rid of that risk (the “insurance premium”). See the Appendix A for a brief description of the certainty equivalence concept, its relation to VoLL, and the willingness to pay to be insured against supply interruptions.

4 Literature review

As previously mentioned, mainly two approaches are used to estimate the cost of a power outage or value of lost load (VoLL) in the literature; stated preferences (surveys) and revealed preferences (see Sanghvi, 1982, Willis and Garrod, 1997; van der Welle and van der Zwaan, 2007; Reichl, 2013; Schröder and Kuckshinrichs, 2015). The stated preference approach means that respondents, in this case firms or households, state their costs from outages or disturbances in the power supply in hypothetical scenarios. Common is that respondents are asked to state either the maximum willingness to pay to avoid a disturbance or outage, or the minimum compensation to accept a disturbance. Another approach is to directly ask what the cost is for a specific scenario (see for example Carlsson, et. al., 2019). The revealed preference approach, on the other hand, make use of observational data on production, electricity use, and prices. Given observational data the cost can in principle be estimated according to the framework given in section 3.

The different approaches have their pros and cons. In the stated preference case, survey design issues typically become crucial. For example, it is critical to ask relevant questions concerning the costs. In some studies, only direct costs in the form of non-recurring expenses are asked for, while in other studies questions about the loss of production is also included (CEER, 2010). Sometimes only "costs" in general terms are asked for, without any further specification, which makes interpretations difficult and uncertain. Since the intension usually is to measure all costs related to a black-out, it is important that both direct and indirect costs are included. It is also important that questions are asked so that it is clear to the respondents what they intend to measure. Not the least, it is crucial that survey protocols are clear on, e.g.; the duration of an outage; when during the day it occurs; and in which season of the year. In addition, a more fundamental issue is whether one should ask about the WTP for avoiding an outage, or the WTA a black-out, in terms of a minimum compensation. Altogether, these issues make comparisons of results from different studies difficult. The main advantage with the stated preference approach is the flexibility in the design of different scenarios concerning, e.g., duration and time of day. As mentioned in the introduction, the hypothetical nature of stated preferences is also its weakness since we cannot be sure that the answers reflect how they would behave in a real situation, especially in cases where the respondents are unfamiliar with supply disturbances and outages because they seldom occur.

The production theory approach, described in the previous section, can be implemented and applied in different ways. The most common approach is to measure the loss of production in terms of lost value added or lost GDP, depending on the aggregation level (De Nooij et.al, 2007, Leahy and Tol, 2007). However, such calculations are based on specific assumptions about the production technology, as shown in the previous section. One advantage with the approach is that it is simple and can be used to estimate outage costs for the economy as a whole, specific regions, specific sectors or for individual companies. Another advantage is that the approach is based on actual behavior of firms. If data at the micro level is available, outage cost at the firm level can be estimated, and in a second and third step, it can be aggregated to the sector level and economy level, respectively. Given data at the macro level, i.e., for the whole economy or only at the sectoral level, only aggregate measures can be estimated/calculated. A disadvantage with the production theory approach is that data usually is aggregated over time to annual data, or at best to monthly data. This means that the approach usually cannot consider that the cost may depend at which time of the year or day an outage occurs.

Below we provide a brief overview of the results from empirical studies that have applied the two approaches above, both for Sweden and for other countries.

A common feature of previous studies is that the cost is normalized with the electricity consumption that is lost (unserved electricity), or with maximum load (power) (Carlsson and Martinsson, 2019). That is, the former is the total cost of an outage or disturbance divided by the amount of electricity lost (€ per KWh), whereas the latter is the outage cost divided by the electric power lost (the cost per KW). The main reasons for doing such normalization are to make estimates comparable between different firms or sectors, and that normalized values are useful in determining the optimal reliability level. However, due to differences in normalization procedure, comparisons between different studies becomes difficult. Furthermore, normalized values can lead to severely biased estimates of the reliability level if the measures to enhance the reliability level affect different sets of electricity consumers that differ in their composition, e.g., some measures may mainly affect industrial electricity consumers whereas a national VoLL is a broad average covering all sectors of the economy.

Because our study concerns outage costs, or values of lost load (VoLL), in Sweden, we start by reviewing the most recent Swedish empirical study (Carlsson et al., 2019). The approach taken in the study is the stated preferences approach where households are asked to state their WTP for avoiding a power outage (of different durations). Respondents other than household representatives are asked about the direct costs of outages that are caused by power outages of different durations. The outage cost is measured in two different units; outage cost in Swedish crowns per duration, and interruption cost per unit of maximum load (MW). In the survey protocol, companies are also asked what type of costs that are associated with an outage, and if they have taken any precautionary measures to mitigate the consequences of an outage.

The results from the survey study show that the most common types of costs for the industry stem from restructuring of activities, that they lose sales, and have costs for restarting production processes. Concerning precautionary measures, 80% answered that no such measures have been taken, whereas 11% answered that they installed back-up generators. The rather large fraction of companies taken no precautionary measures may reflect the fact that outages are rare, i.e., firms perceive their power supply to be highly reliable.

Concerning interruption cost for the Swedish industry, the results reveal, as expected, that it increases with the duration of an outage, i.e., the longer the outage, the higher the cost. Surprisingly, the average outage cost for the industry increases linearly with the durations investigated, and because the alternatives follow a non-linear duration trajectory, the mean cost per minute of outage decreases quite dramatically with duration. According to the results, the mean cost (un-normalized) in the Swedish industry is approximately €500 per minute for a 3-minute outage, and €50 per minute for a 12-hour outage.[6] Perhaps even more surprising is the very skewed distribution of costs; 66% of the responding companies state zero cost for a 3-minute outage, and 29% state zero cost for a 12-hour outage, implying that the median cost is considerably lower than the mean cost. The mean of the normalized cost (cost per KW) ranges between €7 per KW for a 3-minute outage to €190 for a 12-hour outage. However, the median is considerably lower, from 0 to €46 per KW. The results also reveal that the distribution of estimated cost within the industry is not only skewed but also wide, ranging from zero to €160 for a 3-minute outage and zero to €2400 per KW for a 12-hour outage. Part of this heterogeneity in cost can be explained by the size of the company in terms of sales. The mean (median) cost of a 3-minute outage is €15 (0) per KW for firms with a value of sales less than €1 million, and €139 (15) for firms with a value of sales larger than €100 million.

The study by Carlsson et al. (2019) is a replicate of an earlier Swedish study, Carlsson and Martinsson (2006), in which they estimate interruption cost for the year of 2003. The two studies are almost identical, which facilitates direct comparisons. The estimated average cost per KW for a 3 minute and one hour interruption in the study from 2003 is €2.50 and €12, respectively (2017 price level), i.e., about one third of the cost found in the more recent study. As in Carlsson et al. (2019), a surprisingly large share of the firms that responded to the survey stated zero cost (45% and 25%). That the cost is significantly higher in the more recent study may be an indication that firm's have become more dependent on electricity, and more vulnerable to interruptions. Looking back even further in time strengthen the hypothesis of a positive trend over time. Andersson and Taylor (1986) report cost estimates from two early Swedish studies (Svenska Elverksföreningen, 1981); one for the year of 1969 and one for 1980. As in Carlsson et al. (2019) and Carlsson and Martinsson (2006), the cost estimates are based on data from questionnaires. According to the results from the 1969 study, the interruption cost, normalized by the lost load, in Swedish industry amounted to €0.9 for a half-hour interruption, and €2.50 for a two-hour interruption (inflated to the price level of 2017). This can be compared to the estimates for 1980 that uses the same way of measure the cost, which amounts to €3 and €8 respectively, i.e., approximately three times the values in the 1969 study.

Internationally, VoLL for companies has been studied several times (see overviews in Sullivan et al., 1997, van der Welle and van der Zwaan, 2007, Sullivan et al. 2009, Reichl, 2013, Schröder and Kuckshinrichs, 2015). Most studies present the outage cost normalized by unserved electricity. As such, comparisons with the results in Carlsson et al. (2019) are not straightforward. A robust conclusion that can be drawn from the above reviews of the VoLL literature is that estimates vary considerably, depending on country, type of end-user, and methodology used. According to the review by Schröder and Kuckshinrichs (2015), VoLL ranges from a few €/kWh up to € 250/kWh.

[6] The exchange rate used is SEK 10 per Euro.

Two other European studies are de Nooij et al. (2007) and Leahy and Tol (2011) who estimate VoLL for the Netherlands and Ireland, respectively. Both studies use the production function approach, where a sector's cost of a power outage is measured in terms of value added per unit of electricity used (kWh or similar). Leahy and Tol (2011) finds that the outage cost, or VoLL, in Irish industry is approximately € 3-4/kWh, i.e., much lower compared to the household sector. For the Netherlands, de Nooij et al. (2007) estimates of VoLL ranging from € 1.87/kWh (industry) to € 33.50/kWh for government. These estimates also vary to some extent over time and geographically. The normalization approach that is applied, and hence the way VoLL is defined, implies that VoLL will be high in sectors where the electricity intensity is relatively low and vice versa, which explains why VoLL for "government" is more than 10 times higher than VoLL in the pulp and paper industry.[7]

Worth mentioning is also two meta-studies focusing on electricity customers in the US, Sullivan et al. (2009), Centolella (2006), and a study in Israel, Tishler (1993). According to Sullivan et al. (2009) the median value of 28 studies is $ 9/kWh for large companies and $ 35/kWh for small companies. A conclusion that can be drawn from the review in Sullivan et al. (2009) is, as in the studies mentioned above, that VoLL varies considerably between studies. Centolella (2006) reviewed 24 studies conducted for "the midwest region" in the US. Also, here the variation is considerable, with a median value ranging between $ 29/kWh and $ 42 kWh. The analysis in Tishler (1993) differs from most other studies since it allows firms to consider its ability (or lack of ability) to respond to a random outage. In Tishler (1993), who estimate the expected outage cost in Israel, the beginning and duration of an outage is a random variable. The results are qualitatively similar to the results in other studies that are using the production function approach (de Nooij et al., 2006, Leahy and Tol, 2011), i.e the outage cost per KWh is relatively low in energy intensive industries sectors, and high in not so energy intensive sectors.

To summarize, it is fair to say that the previous literature is quite extensive, but that comparisons between the different studies are difficult. One reason is that there seems to be no common ground of what to measure, and how. Some studies measure and report the actual outage cost (unnormalized) in terms of loss of consumer surplus or value added, whereas other normalize the cost with either unserved amount of electricity or the maximum effect, or load. Another reason is that the methodology differs between studies, as well assumptions regarding the duration of outages and at what time of day and year they occur. However, what seems to be quite evident, since there exist comparable studies, is that the cost of interruptions in the Swedish industry seems to have increased over time. One plausible explanation to this is that the industry has become more dependent on a continuous flow of electricity, and therefore more vulnerable to interruptions.

[7] "Therefore, when electricity is scarce and needs to be rationed, the economic cost is lowest when firms in the construction sector, the government and households are cut off as little as possible, and manufacturing is cut off first. The economic costs are lowest when the best (i.e., the largest) customers are treated worst." (De Nooij et al. 2007, p. 287).

The approach taken in this study is essentially a revealed preference approach, complemented with a small qualitative survey to selected companies. As such it is most comparable to the studies by de Nooij et al. (2006) and Leahy and Tol (2011).

5 Cost of electricity interruptions in Swedish industry

5.1 EMPIRICAL APPROACH

The objective in this section is to empirically assess the costs associated with interruptions or outages in electricity supply to the Swedish industry. The assessment departures from the conceptual framework laid out in section 3. The main empirical approach is to use actual observations at the firm level, i.e., actual data on electricity consumption, production and value added. This approach follows to a large extent what has been called the production function, or revealed preference, approach, discussed in previous sections (see de Nooij et al., 2007 or Leahy and Tol, 2011). As discussed, there are some advantages, but also disadvantages, with this approach. One obvious advantage is that the estimates are based on observed behavior, contrary to the commonly used stated preferences approach. A disadvantage is that we normally cannot consider how duration of an interruption affects costs, and how time of the day or season for an interruption affect the cost. Furthermore, as discussed in section 3, assumptions have to be made concerning flexibility of labor and other inputs. Concerning the latter, what can be done is to estimate upper and lower limits of the cost (see section 3).

Also discussed in previous sections are that consequences and costs of an outage may vary considerably both between and within sectors, and even between production sites within firms. One implication of this is that cost estimates based on rather aggregated data, and/or from generic questionnaires that do not target specific sites and key persons therein, may be biased or at least be subject to large uncertainty. Because of this, our empirical analysis is complemented in section 6 with a qualitative analysis based on a questionnaire targeting keypersons in a small number of industrial companies. The objectives with this qualitative study are to identify firm-specific aspects that are not revealed or cannot be captured by annual firm level data, to get a more qualitative picture of how firms perceive the consequences of power outages, and how that aligns with the microeconomic production data approach used in the quantitative analysis.

The remaining of this section is structured as follows: In the next subsection, 5.2, we present the underlying data that is used. The estimates of the interruption costs are presented and discussed in section 5.3. Section 5.4, finally, contains a concluding discussion of the results.

5.2 DATA

The data used to estimate the cost (value) of supply interruptions is firm level data from the Swedish manufacturing industry (including mining) during the years 2004 to 2016. The data is provided by Statistics Sweden through the MONA platform. The data base used is includes data on accounting variables (value added, profits, labor use, assets, etc.), energy use, emissions to air, and environmental management. Here we only use a small part of the data base focusing on value added, electricity consumption and, to some extent, profits. More details on this below.

The firms are divided into different sectors according to the following 3-digit SNI2007 classifications:

"Basic iron and steel" (BIS) – SNI2007 241:245
"Chemical" - SNI2007 191:192, 201:206
"Electro" – SNI2007 261:268, 271:275, 279
"Fabricated metal products" (FMP) – SNI2007 251:257, 259
"Food" - SNI2007 101:110, 120
"Machinery" (Mach) – 281:284, 289
"Mining" - SNI2007 051:052, 061:062, 071:072, 081, 089, 091, 099
"Motor vehicles" (MV) – SNI2007 291:293
"Printing" – SNI2007 181:182
"Pulp and paper" (P&P) – SNI2007 171:172
"Rubber and plastic" (R&P) – SNI2007 221:222
"Stone and mineral" (S&M) – SNI2007 231:237, 239
"Textile" – SNI2007 111:133, 139, 141:143, 151:152
"Wood" - SNI2007 161:162

This is a rather aggregated or "crude" division of the manufacturing industry, implying substantial heterogeneity for some subsectors in terms of specific products produced, technology, firm size, and not the least electricity use. The sectors "fabricated metal products", "machinery", and "food" are very heterogenous, while other sectors are more homogenous, such as "pulp and paper" and "stone and mineral". We choose to divide the manufacturing industry into these sectors because of convenience (based on SNI-codes at the 3-digit level) and the fact that many prior studies on Swedish manufacturing industry use this sectoral partition, or at least very similar partition.

In Table 5.1 we present electricity consumption (in GWh), value added (in MSEK), and number of firms in each sector, which are the variables of particular interest in this study, for the time period 2004 to 2016. As Table 5.1 reveals, "pulp and paper" (P&P) is by far the biggest electricity consuming sector in the manufacturing industry, followed by the "basic iron and steel" (BIS) and "chemical" sectors. As can be seen, electricity consumption varies substantially between years, and it seems like 2016 is a particular low electricity use year for BIS and P&P. The long-run time trend in most sectors is that electricity use is decreasing over time. For P&P the lower electricity consumption for the later years (2013 and onwards) may be explained by a higher level of own-produced electricity, i.e., bioenergy from production residues, mainly black liquor, but also wind, hydro, and residue heat from production process that is transformed into electricity (about 40% is own-produced today). In 2021, about 15% of Sweden's total electricity use come from the forest industry.

Value added (VA) in Table 5.1 is defined as profits plus labor and capital cost (or revenues minus material and energy input). Table 5.1 shows that the largest value added is in "motor vehicles" (MV) sector, followed by "machinery" (Mach.), "food", "fabricated metal products" (FMP), and "chemical". Some sectors, e.g., "mining", show large variation in value added over time, while the variation in electricity consumption is more stable. This implies that electricity use is decoupled from the production activity to some extent, meaning that part of the electricity cost can be viewed as a "fixed cost" (e.g., lighting, heat).

Number of observations simply tells us how many firms there are in each sector a specific year. In 2016 FMP has the largest number of firms, followed by "machinery and food". This is not to be interpreted as this sector being large in terms of aggregated value added, its simply shows that these sectors contain many small firms. The sectors "basic iron and steel", "mining" and "pulp & paper", on the other hand, consist of few relatively large firms.

Table 5.1. Electricity consumption, value added, yearly number of observations, 2004-2016.

Annual electricity consumption in GWh

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BIS	6388	6395	6226	4756	5781	3787	4936	5513	5393	5611	5154	5437	3528
Chemical	3523	3279	3528	3175	3634	2617	3461	3495	3630	3531	3339	3501	3474
Electro	532	515	531	468	413	372	368	372	339	316	316	323	313
FMP	1564	1520	1666	1753	1667	1309	1448	1454	1443	1374	1350	1322	1252
Food	1255	1336	1366	1394	1439	1229	1386	1452	1481	1428	1451	1557	1477
Mach.	1475	1585	1413	1138	1247	1092	1144	1179	1102	1065	1021	1027	1013
Mining	1519	1612	1669	1286	1897	733	1975	1956	2081	2028	2021	1912	1914
MV	1547	1583	1565	1307	1533	981	1208	1322	1237	1266	1248	1305	1238
Printing	422	403	407	309	306	258	241	238	223	190	169	172	138
P&P	16590	16558	17517	16609	17288	16444	16855	16651	16639	14423	12853	12859	11711
R&P	935	913	938	874	896	806	889	872	846	849	832	865	850
S&M	801	818	865	856	886	704	743	737	685	667	678	667	690
Textile	263	264	229	215	213	165	170	179	182	177	187	199	201
Wood	1322	1313	1404	1438	1373	1258	1304	1296	1192	1130	1053	1131	1138

BIS: Basic iron and steel. FMP: Fabricated metal products. Mach.: Machinery. MV: Motor vehicles. P&P: Pulp and paper. R&P: Rubber and plastic. S&M: Stone and mineral.

Value added in MSEK, adjusted by sector's producer price index (2015 = 100)

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BIS	14105	17836	22739	24467	23448	9027	12729	17550	14885	13517	15572	15488	16517
Chemical	36850	45804	48462	15342	19144	18792	25191	24413	26359	23370	22991	32961	29501
Electro	34258	31996	32350	21298	20742	18494	18475	18442	15483	15351	15457	16986	18888
FMP	17954	21146	24369	28320	31771	23976	25811	29728	30484	29335	29910	31813	31119
Food	20981	21191	22722	23188	27305	27575	29132	31469	32687	31735	33336	35994	36309
Mach.	28729	35042	41379	45620	50706	42133	51917	58675	53231	45590	44000	53097	52548
Mining	5352	9608	13551	13222	15119	5684	21135	25418	21983	17487	16251	14850	17051
MV	43607	43472	44846	49977	44804	23122	43151	44907	41050	37832	41649	64569	65049
Printing	10065	9563	10786	6442	6907	5908	5997	6367	5879	5302	5094	5485	4382
P&P	25376	21833	26192	27698	25310	26820	30408	30032	24504	22283	25988	32870	27693
R&P	6786	7728	8840	9575	9352	8237	8691	10067	9951	9542	10332	11064	11062
S&M	6294	6602	7857	9253	9806	8268	9127	10526	9479	9897	9237	11685	10962
Textile	2789	2804	2845	2787	2545	2116	2444	2423	2303	2019	2397	2710	2820
Wood	9584	9901	13594	20084	12896	12482	15468	12375	11655	12218	14036	15286	15874

Number of observations in sectors

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
BIS	108	118	121	116	133	125	121	125	126	123	118	116	110
Chemical	189	198	198	154	165	152	157	160	161	157	154	165	146
Electro	417	440	456	358	376	374	338	346	330	336	326	327	318
FMP	1043	1169	1271	1330	1426	1364	1231	1262	1317	1297	1252	1271	1147
Food	367	411	445	458	475	473	493	509	517	498	483	523	456
Mach.	664	733	763	709	731	696	646	650	643	627	596	604	573
Mining	35	37	44	46	53	51	51	52	51	46	45	41	38
MV	169	191	192	199	214	198	199	193	190	186	186	180	170
Printing	397	394	399	283	295	269	240	232	224	205	198	191	167
P&P	137	135	144	141	144	147	137	132	130	126	122	129	114
R&P	283	296	315	313	326	320	302	298	301	293	284	289	274
S&M	117	135	139	146	157	156	143	139	140	133	132	139	129
Textile	121	121	118	112	118	121	111	111	113	101	94	97	86
Wood	392	406	442	448	466	445	434	426	418	382	369	371	354

To summarize, there is large variation between industrial sectors with respect to both electricity use and value added. Also clear from Table 5.1 is that there is a stagnation of electricity use over time, whereas value added have a positive time trend. This implies that electricity intensity in terms of electricity use per unit of value added has a downward trend; more value is produced with less electricity.

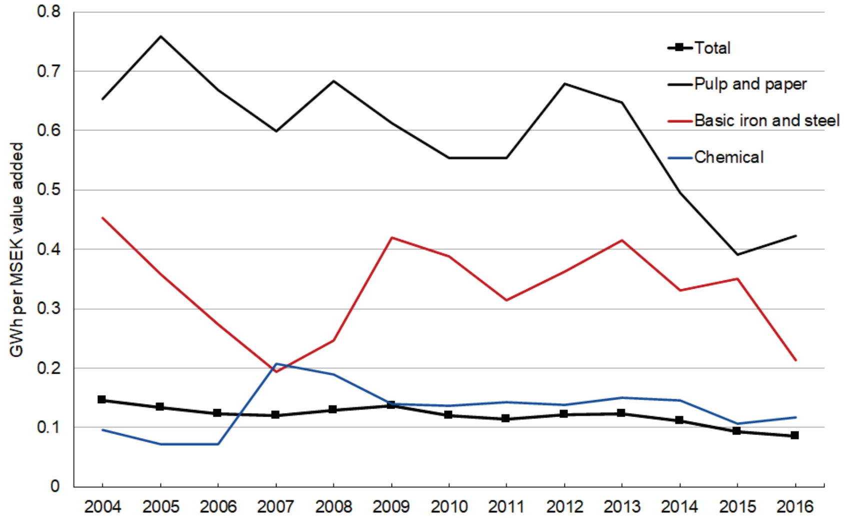

Figure 5.1. Electricity intensity in the Swedish manufacturing industry, 2004 – 2016. GWh per MSEK value added.

In Figure 5.1 it can be seen that the electricity intensity for the industry as a whole have decreased by approximately 40% between 2004 and 2016. A similar decrease can be noted for the pulp and paper industry. Also, the basic iron and steel industry reveals a downward trend, although less pronounced. The rather strong downward trend for pulp and paper can to some extent be explained by an increase in self-generated electricity within the sector. Figure 5.1 also reveals that the electricity intensity in the electricity intensive industry follows the business cycle to a large extent, implying that production and electricity use is less decoupled in these sectors.

Electricity is used for different purposes in different industries. For some industries electricity serves more or less as a fixed input that is independent of variations in production, whereas in other sectors electricity serves as a necessary energy source in the production process. In Figure 5.2 electricity consumption by purpose for the different industrial sectors is presented. The pulp and paper industry are using electricity mostly for impulsion, lighting, and heat. Basic iron and steel use a substantial part of their electricity for electrolysis (green) and furnaces/melting (yellow). Chemical and a few other sectors also use electricity for electrolysis to some extent. By far the most common use of electricity is impulsion, lighting, and heat (purple). Lighting and heat are to a large extent independent of short run fluctuations in production level, implying that sectors with a large heating and lighting share will show up large fluctuations in electricity intensity.

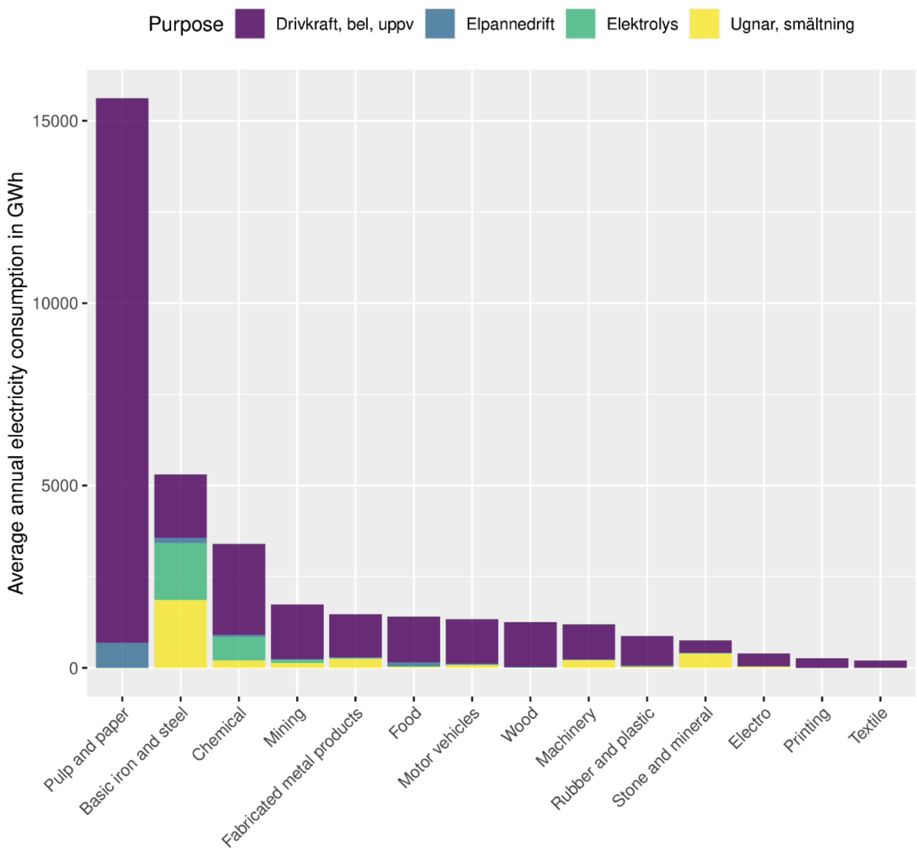

Figure 5.2. Average annual electricity consumption in GWh by use/purpose 2004-2016. Drivkraft, bel, uppv: Impulsion, lights, heat. Elpannedrift: Electric boiler. Elektrolys: Electrolysis. Ugnar, smältning: Furnaces, melting.

5.3 COST OF SUPPLY INTERRUPTIONS

The costs of supply interruptions are measured in two different ways below (following de Nooij et al., 2007). As discussed above, the approach has its underpinnings in production economics and specifically production functions; hence it is called the production function approach.

Two different measures of the interruption cost will be considered. The first, and most common in the literature, is the value per unit of electricity that is not delivered; this is the *value of lost load* per KWh, hereafter denoted VoLL. It is calculated as the value added per KWh electricity consumed (per year in this case). This measure is useful if, for example, an electricity (supply) shortage happens. In this case some users may have to be disconnected (a sort of rationing). The total costs of an interruption can then be minimized by disconnecting the users with the lowest VoLL.

However, a property with this measure is that the implied duration of the interruption will differ between firms and sectors, which causes a problem if we want to make cost comparisons for an interruption with a given duration. The reason is that the duration of a 1 KWh lost load in one firm/sector in general differs from the duration of a 1 KWh lost in another firm/ sector. To see this, denote electricity use without any interruption by q^*, and electricity use if an interruption occurs by q^a. Furthermore, denote the fixed electricity use per hour by q^h, and assume that the firm is active every hour of the year, 8760 hours. The lost load for each firm/sector as a result of an interruption can then be expressed as:

$$\Delta q_i = q_i^* - q_i^a = q_i^h \cdot 8760 - q_i^h \cdot (8760 - t_i^a) = q_i^h \cdot t_i^a, \qquad i = 1, \ldots N \text{ (firms/sectors)}$$

Setting the lost load, Δq, to 1 (KWh) for all firms/sectors then gives:

$$t_i^a = 1 / q_i^h \cdot, \qquad i = 1, \ldots N \text{ (firms/sectors)}$$

That is, the duration that corresponds to a 1 KWh lost load depends on the hourly electricity use, which differs between firms/sectors. As a result, aggregation of costs, resulting from an interruption of a given duration, over firms, sectors and the whole economy cannot be done. This in turn implies that it cannot be used in a benefit-cost assessment of potential measures to mitigate the risk of an interruption of a specific duration. In such case a cost per unit of duration should be used instead.

Due to the specific caveats with the VoLL measure above we therefore also calculate the cost per unit duration, or cost per hour (CpH), which is simply value added per hour production lost in an outage. As above we assume that all firms are operating 8760 hours per year, which probably is not true for many firms in our data. But for larger industrial and electricity intensive firms it is probably a reasonable assumption. As pointed out, this value is useful in benefit-cost assessments, for example when making decisions about investments in network reliability. If the damage caused per hour interrupted supply in certain regions or sectors is high, the benefits of supply reliability investments in these regions/sectors are also high.

For each measure, VoLL and CpH, we calculate lower and upper limits of the cost, according to equations (4) and (7) in section 3. The lower limit is the case when both labor and material input is completely flexible in the sense that labor can be dismissed, and material can be stored without any losses (equation 4), i.e., the cost equals the loss in profit due to the production interruption. The upper limit corresponds to the case when labor cannot be dismissed, but material can be stored for future use (equation 7). This upper value corresponds to the loss in value added (loss in profit plus labor cost).[8]

[8] What we here denote upper limit is what we in section 3 denote intermediate value. The upper limit in section 3 equals the value added plus the material cost, i.e., it corresponds to the case when material is spoiled as a result of the interruption. Due to lack of data on material cost this value is not calculated.

5.3.1 Value of lost load (VoLL)

Table 5.2 presents the average upper and lower limits of VoLL (H, L) for firms in each sector for the years 2004, 2008, 2012, and 2016. As mentioned above the lower limit (L) is the case when both labor and material input is flexible, i.e., an interruption in production as a result of an outage implies that labor can be dismissed without costs. Given this Table 5.2 reveals that the outage cost is relatively small, reflecting that the labor share of value added is high. As can be seen in Table 5.2 the lower limit average VoLL in the mining sector is even negative in 2008, reflecting negative profits for many mining firm(s) that year. The reason for this is quite dramatic decrease in metal prices in 2008, because of the financial crisis. The average lower limit VoLL for the industry as a whole have increased from approximately SEK 5 per KWh in 2004 to about SEK 7, i.e., about 10-15 times the current price of electricity.

The assumption of a completely adjustable labor force, however, is an unreasonable assumption for most firms, considering that outages are short and rarely exceeds a couple of hours. Therefore, the upper limit VoLL may be of more interest.

Table 5.2. High (H) and low (L) VoLL estimates for sectors, 2004, 2008, 2012 and 2016. SEK/KWh.[a]

	2004		2008		2012		2016	
	H	L	H	L	H	L	H	L
Electro	130.91	11.33	126.45	14.15	121.49	12.69	155.69	16.51
Mining	44.57	2.81	109.78	-6.64	113.43	9.51	118.19	29.05
Machinery	54.45	6.33	67.37	7.77	69.85	8.10	96.30	12.06
Stone & mineral	49.22	4.61	65.68	7.24	63.45	6.64	83.68	7.22
Textile	44.70	3.77	55.41	6.25	64.36	3.75	74.61	8.67
Printing	64.92	4.07	46.40	2.09	56.35	3.69	63.80	4.60
Motor vehicles	38.24	3.44	44.92	3.85	50.79	3.36	61.66	5.93
Fabricated metal	32.95	2.21	46.61	4.85	50.01	3.90	59.50	5.30
Chemical	31.91	6.46	37.24	6.81	46.35	6.70	55.30	3.68
Wood	21.02	1.45	33.48	2.24	36.79	2.11	54.25	6.89
Rubber & plastics	26.78	2.85	28.37	2.69	33.69	2.54	45.18	6.12
Basic iron and steel	17.58	4.89	31.94	3.66	33.75	1.38	41.59	4.46
Food	23.90	10.36	25.83	0.58	33.38	2.06	38.03	2.50
Pulp & paper	22.74	2.61	24.36	2.42	26.87	3.32	29.13	2.29
Industry	*46.34*	*4.91*	*51.24*	*4.93*	*54.29*	*4.77*	*68.76*	*7.19*

[a] L = profit/KWh , H = value added/KWh

In Table 5.2 it can be seen that in 2016 the highest cost according to the upper limit VoLL measure are found in the "electro", "mining", and "machinery" industry. The lowest average VoLL is found in electricity intensive sectors as "pulp & paper", "basic iron & steel". This may seem counterintuitive at first but remember that VoLL simply measures the value added per consumed KWh of electricity. This implies that VoLL is decreasing in electricity use and increasing in value added. More or less all sectors show upward trends in VoLL. Firms in "mining", "basic iron & steel", and "wood", for example have on average almost three times higher VoLL in 2016, compared to 2004. The main reason is that value added in these sectors have increased at a much faster rate than the electricity use. The average VoLL for firms in the remaining sectors show a more moderate positive trend. Table 5.2 also reveals that apart from the trend, variability between years is not very pronounced for the upper limit measure, in contrast to the lower limit measure. The main reason for this difference between the upper and lower limit is that business cycles tend to affect firm profits more than value added, reflecting a rather non-flexible labor force. For the manufacturing industry as a whole table 5.2 show that VoLL have increased from SEK 46 per KWH to SEK 69, for the upper limit, i.e., an increase of about 48%, which can be compared to the current electricity price of about SEK 0.50 per KWh. This general positive trend is a result of an increase in value added in the industry as a whole, and a decrease in electricity consumption over the period we study. This indicate that the manufacturing industry has become significantly more vulnerable to electricity supply interruptions during this period in terms of VoLL.

As pointed out, these VoLL estimates should be interpreted with care. Considering the estimates per se in Table 5.2, they represent averages over sectors. As we pointed out, however, there is considerable heterogeneity within sectors, implying potentially large variations of VoLL also within sectors.

The within-sector variation of VoLL is illustrated by the box-whiskers graph in figure 5.3.

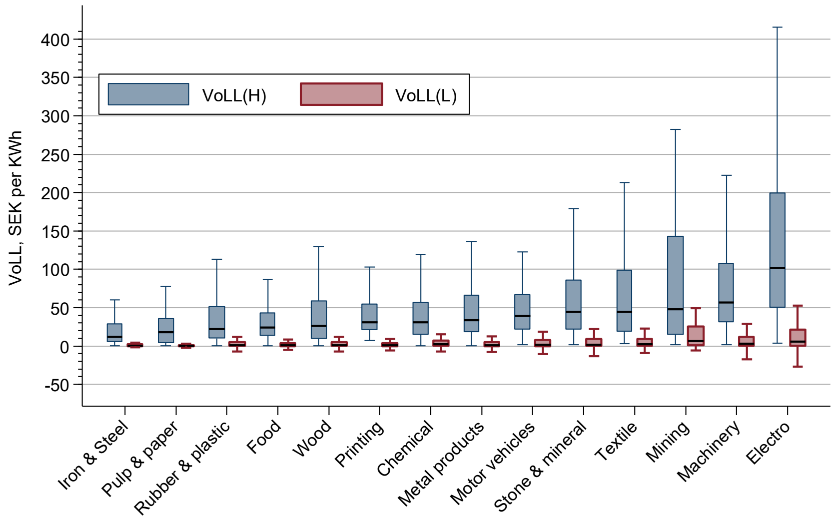

Figure 5.3. VoLL estimates 2016 within each sector. SEK per KWh.[9]

As revealed by figure 5.3 there is considerable variation within sectors, and the variation is increasing with the median. For the pulp and paper industry, upper limit VoLL ranges between SEK 2 and SEK 80 per KWh with a median of SEK 18,

[9] The upper and lower edges of the "box", or rectangle, is defined by the lower and upper quartiles, and the vertical line inside the box is located at the median. The upper end-point of the "whiskers" (upper adjacent value) is defined by the observation not exceeding the upper quartile observation, plus 1.5 times the difference between the upper and lower quartile. The lower end-point (lower adjacent value) is defined by the lower quartile observation, minus 1.5 times the difference between the upper and lower quartile. Observations outside the "whiskers" are defined as outliers and are not included in the graph.

whereas it varies from a few SEK per KWh to more than SEK 400 in the electro industry.[10]

5.3.2 Cost per hour of outage (CpH)

As pointed out above, VoLL estimates should be interpreted with care also because of the way VoLL is defined. As VoLL is defined it may be useful in a rationing context, but not in a benefit-cost context where investments to mitigate the risk of say a one-hour outage is to be assessed. The reason is that VoLL, as defined above, corresponds to an outage duration that varies between firms, because of differences in electricity intensity. Because of this, the outage cost in terms of cost per hour is calculated, denoted CpH. As above we can calculate upper and lower limits of CpH. The upper limit CpH is calculated as value added divided by the number of operating hours, whereas the lower value is calculated as the profit divided by the number of operating hours. Unfortunately, we do not have data on operating hours. To overcome this, we simply assume that all firms are operating 24 hours per day all around the year, summing up to 8760 hours. This is of course a very strong assumption since some sectors may contain a substantial share of firms not operating all hours of the year. But for large process firms such as steel mills and paper and pulp mills, the year around operation assumption is reasonable Overall, given this assumption, CpH should be interpreted as a lower limit. The results are presented in Table 5.3.

Table 5.3. Average cost for a one-hour outage in each sector (CpH), SEK.

	2004		2008		2012		2016	
	H	L	H	L	H	L	H	L
Mining	17456	5294	32564	10138	49206	18722	51224	5437
Motor vehicles	29455	6189	23900	1980	24664	3637	43681	4179
Pulp & paper	21144	3732	20064	5459	21517	2820	27730	-330
Chemical	22257	7251	13245	2600	18690	4411	23066	90
Basic iron and steel	14909	4260	20126	2707	13485	-1972	17141	925
Machinery	4939	1005	7918	1319	9450	1818	10469	930
Stone & mineral	6141	620	7130	1516	7729	1087	9701	1564
Food	6526	3287	6562	612	7217	1350	9090	739
Electro	9378	824	6297	-99	5356	797	6780	818
Wood	2791	170	3159	88	3183	-77	5119	448
Rubber & plastics	2737	252	3275	305	3774	252	4609	502
Textile	2631	273	2462	228	2327	147	3743	407
Fabricated metal	1965	218	2543	437	2642	310	3097	274
Printing	2894	189	2673	101	2996	201	2995	124
Industry	*6756*	*1427*	*6740*	*947*	*7346*	*1130*	*9502*	*733*

[a] $CpH_i = \overline{VA_i} \cdot /8760, \quad \overline{VA_i} = \sum_k VA_{k,i} \,/\, NOBS_i$

$VA_i =$ value added in sector i, $NOBS_i =$ number of firms in sector i

An immediate observation from the results in Table 5.3 is that the cost for a one-hour outage varies considerably, depending on sector. However, what it largely reflects is average firm size, and hence variations in value added. We see that the cost for firms in the mining and motor vehicles industry are very high, compared

[10] Means, medians and quartiles for 2004, 2008, 2012 and 2016 are presented in Table A1 in the appendix.

to the cost for firms in the other sectors. This, however, mostly reflects that the firms in these sectors are big and therefore generates large value-added values.

The box-whisker plots in figure 5.4 give an illustration of how the cost for a one-hour outage varies, depending on firm size and sector. Firms are divided into six different size classes, in terms of number of employed.

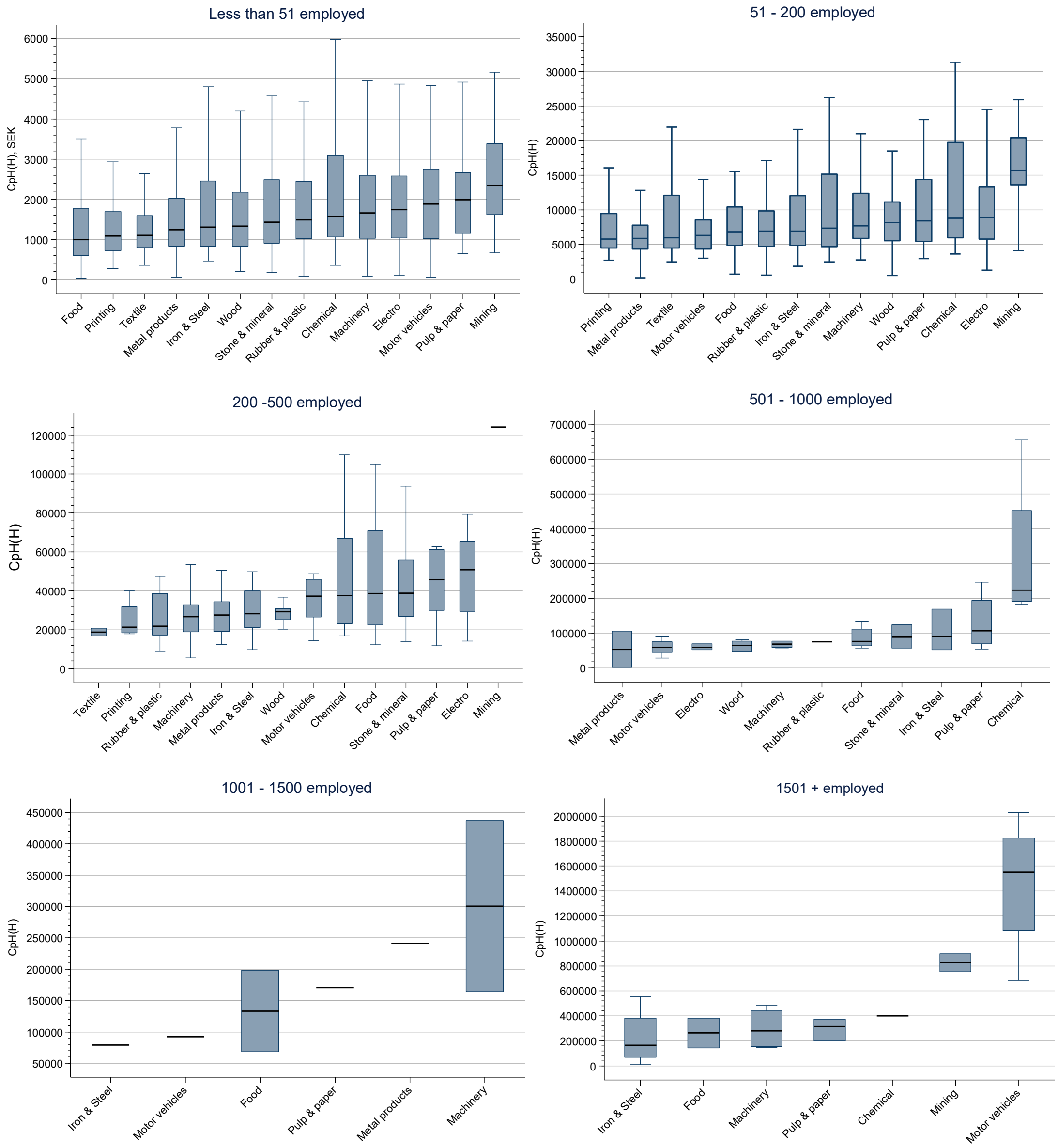

Figure 5.4. Cost for a one-hour electricity outage (value added/8760). SEK.[11]

Figure 5.4 reveals the fact that cost per hour (value added) increases with firm size. The larger the firm, the higher value added and hence a higher cost for an outage. To get a more precise picture of how the cost for firms of equal size differs between sectors a box-whiskers plot over cost per employee for the various sectors in 2016 is presented in figure 5.5.

[11] Calculated as value added per hour of operation, with the assumption that all firms operate 8760 per year.

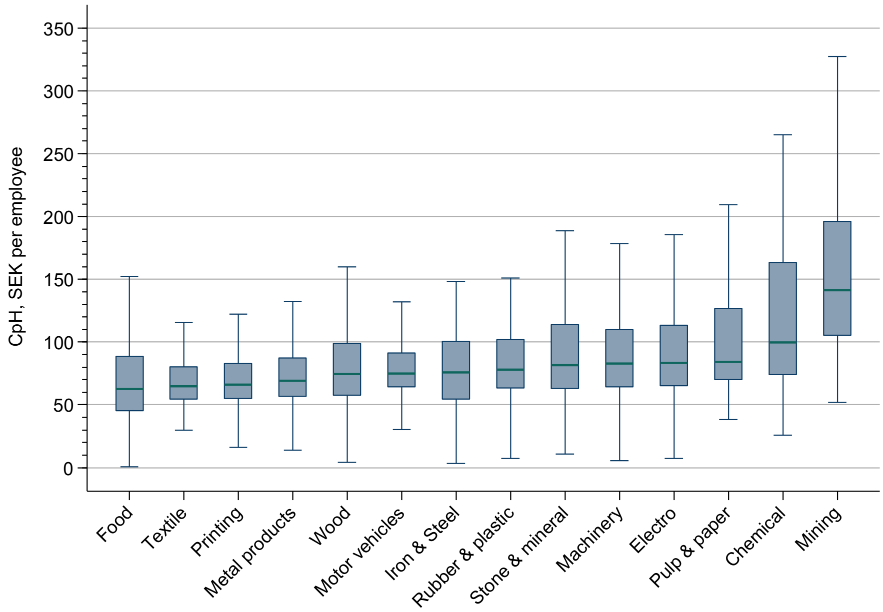

Figure 5.5. Cost per employee for a one-hour electricity outage (value added/8760). SEK.

From Figure 5.5 we see that the median cost per employee ranges from about SEK 65 per employee in food industry to about SEK 140 in mining. Interesting to note is that the cost per employee is fairly sector-independent, mining excepted. Concerning variation within sectors Figure 5.5 shows no big differences between the different sectors. Median CpH per employee for the industry as a whole is about SEK 74 and the mean is SEK 87. The lower and upper quartiles for the whole industry are SEK 59 and 99 respectively.[12]

5.3.3 Some concluding comments on the Swedish VoLL and CpH estimates

Earlier studies on VoLL, appropriate to compare our results to, are de Nooij et al. (2007), Leahy and Tol (2011), and Carlsson et al. (2019). The studies by de Nooij et al. (2007) and Leahy and Tol (2011), who estimate VoLL for the Netherlands and Ireland respectively, are interesting since they use the same approach as here, i.e., the so-called production function approach, which means estimating a sector's value added per unit of energy used (KWh or similar) in order to measure a sector's "exposure" to power outages.

According to Leahy and Tol (2011), VoLL in Ireland is largest for households, €18/KWh (SEK 180), and that VoLL varies depending on what time of day, which day of the week and which month it is measured. VoLL in the Irish industry is estimated at € 3-4/KWh, i.e., much lower compared to the Irish household sector.

For the Netherlands, de Nooij et al. (2007) estimates VoLL to € 1.87/KWh (approximately SEK 19/KWh) for the manufacturing industry. As in Leahy and Tol (2011) they find that the industry VoLL is significantly lower than VoLL in other sectors in the economy, including the household sector. According to de Nooij et al. (2007) VoLL in the government sector amounts to € 33.50, almost 20 times

[12] Means, medians and quartiles for CpH per employee in 2016 are presented in Table A2 in the appendix.

industry VoLL. As discussed above this reflects that the industry is more electricity intensive than the governmental sector.

Results for Swedish industry in year 2016 show that VoLL varies between € 0.23 – 2.91 per lost KWh (SEK 2.29 – 29.13) on average in the pulp and paper industry, to € 1.65 – 15.57 (SEK 16.51 – 155.69) in the electro industry. For the manufacturing industry as a whole, VoLL range on average between € 0.72 – 6.88 (SEK 7.19 – 68.76). The lower bound corresponds to the loss in profits, while the upper bound corresponds to the loss in value added. Thus, the comparison that can be made to the results in Leahy and Tol, and de Nooij et al. are the upper bounds. Comparing the upper bounds for Sweden with de Nooij et al. (2007) and Leahy and Tol (2011) reveals that the Swedish VoLL is about the same magnitude as VoLL in the Irish industry found in Leahy and Tool, and slightly higher than the value found in de Nooij for the Netherlands. What this essentially says is that the Swedish industry generates about the same value added per unit of electricity as the Irish industry, but slightly more value added than the industry in the Netherlands.

More interesting, perhaps, is to compare the values found here with the results in Carlsson, et al. (2019) who estimate VoLL in Sweden using a stated preference approach in which they ask firm representatives about the direct cost caused by power outages of different durations. They measure the outage cost in two different units; cost in SEK per duration, and cost per unit of maximum load (KW) (denoted normalized cost). According to the results in Carlsson et al. the normalized average cost for a one-hour unannounced outage amounts to € 25 per KW (SEK 248), which is about 3 times higher than industry average VoLL found in this study. However, the normalized cost in Carlsson et al. is not directly comparable to the VoLL calculated in this study because of different normalization factors. Carlsson et al. normalize the cost with the maximum load, while we in this study in principle normalize with the average load. Suppose that the firm operates every hour at full capacity, implying that power need in every hour is the same. Given this, the maximum load equals annual electricity use divided by the total number of hours in a year, 8760, which also equals the average load. This is the normalization factor used in this study. Carlsson et al., however, base their normalization factor on stated maximum load. For some industries, the stated maximum load use may be close to average load, especially for large process industries, but for others the difference can be considerable. As a result, even if cost per hour outage is equal, we would expect VoLL to differ between the studies in the sense that the estimate in Carlsson et al. is higher than in this study (since max load by definition is greater or equal to the average load).

Concerning cost per hour (CpH) the results in this study can be compared to the results in Carlsson et al. Here we found that the cost (value added) per hour is € 950 (SEK 9502), averaging over the industry, which can be compared to € 4000 in Carlsson et al., i.e., about 4 times higher. The median, however, is almost the same, € 194 (SEK 1935) in this study and € 200 (SEK 2000) in Carlsson et al. One explanation to the quite big difference in the average value may be that a one-hour outage not only causes lost production in that hour, as it is measured here, but also other types of costs after the outage as may be captured in Carlsson et al. This is to some extent confirmed in a questionnaire to a small sample of firms, which we report in the next section. Thus, it is reasonable to believe that the cost calculated as the value added per hour underestimates the true cost. Another possible reason may be linked to the fact that the estimates in this study are based on revealed preferences, whereas Carlsson et al. employ a stated preference approach where firms are asked questions about hypothetical scenarios. Previous literature (Loomis, 2011), that compare behavior in hypothetical and real market situations (revealed preferences), finds that that there is a hypothetical bias of factor three, i.e., on average stated preferences approaches overestimates the WTP with 300 percent. Finally, the difference between the results here and those presented in Carlsson et al. may be more of a statistical nature. This study includes in principle all firms, whereas Carlsson et al. used a stratified sample that generated 750 responses in total. One third of the responding firms was relatively large firms with a turn-over larger than SEK 100 million, whereas small firms up to 10 million in turn-over was only 15%. This implies a clear overrepresentation of large firms since the size distribution of firms are very skewed in the sense that the share of small firms is very large. This may explain part of the difference between the mean values, and the similarity with the median.

6 A qualitative assessment of the microdata approach

As described in previous sections, the cost of power outages may appear straightforward to calculate from a technical and theoretical perspective. In practice however, production processes and industries are very heterogenous. In some cases, it might be reasonable to assume that an outage of, say, one hour corresponds to the lost production value of this hour. In other cases, however, a one-hour outage might correspond to an interruption in production processes for several hours, days, or perhaps weeks. This means that the estimates presented in the previous section should be interpreted with care and be viewed as conservative estimates, as also pointed out.

To get a better understanding of how individual firms may be affected and respond to an electricity outage, a survey directed towards a small sample of firms in different manufacturing sectors in Sweden was conducted. The nature of the survey was mostly qualitative with only a few quantitative questions. The aim of the survey was thus not to provide a direct answer to the question about the outage cost in the Swedish industry, but rather to serve as a qualitative complement to the estimates in the previous section.

The questionnaire was sent out to 25 firms in different sectors. The firms targeted was not selected randomly, but rather to cover several industrial sectors and firms of different sizes. In total, 17 completed questionnaires were collected by November 2020. The responses represent several industries such as food industry (4), mechanical production industry (2), pulp & paper (1), sawmill (1), petrol chemical (3), chemical (medicine) (1), metal/mining (3), cement (1), floor (plastic) (1). The invitation to the questionnaire was sent to production site representatives. In some cases, the contact person was the site manager, and in some cases the person responsible for energy issues. In the invitation we informed about the purpose and stated a focus on costs and consequences associated with power outages with varying duration. It was made clear that the information collected would contribute with a qualitative picture and not to be used for detailed calculations. Moreover, the purpose was to keep the sites anonymous and to not disclose identity.

The questionnaire consisted of three different parts. The first part asked about production values and number of employees. The second part had questions related to electricity supply reliability, experience of outages, to what extent they have specific action plans for outages, if specific measures have been taken to mitigate the consequences of an outage, etc. The third part targeted consequences for production processes and activities given outages. Specific attention was given to consequences for production, labor use and costs, handling of material inputs and storage of finished goods.

Given presumably very heterogenous production processes and rather few firms surveyed, the questionnaire allowed for flexibility and opportunities to comment and elaborate on the stated answers. We asked for answers to reflect the production site, and not the whole company (if not the same), meaning that focus was turned to representatives at a production site. In line with these arguments, and that it was not reasonable to collect large number of observations, the questionnaire and answers are very much qualitative in its nature and of more anecdotal character. That said, we still believe this type of information is relevant and necessary to support, discuss and understand the principles for calculating the value of lost load and related measures.

Descriptive statistics for the sites in the sample are presented in table 6.1. As can be seen there is a considerable heterogeneity concerning firm (site) size. The number of employed at the sites ranges from 20 to 1300, with an average of 399. The total annual value of production ranges from SEK 34 million to SEK 12 500 million, with an average slightly below 3 000 million. The variation between firms is also revealed by the production value per employee, which varies between SEK 1.4 to 20 million, with a mean of approximately 6.2 million.

Table 6.1. Descriptive statistics.

	Mean	Min	Max
Number of employed	399	20	1 300
Production value (sales value), SEK 1000	2 973 438	34 000	12 500 000
Production value per employed, SEK 1000	6 173	1 360	20 000

The second part of the questionnaire contained questions about their perceptions about electricity supply reliability and experience of outages, consequence analysis, mitigation plans, etc. According to the results, five sites reported a perceived improvement in supply reliability during the last five years, two a detoriation, while the rest reported neither or. All sites but two had experienced power outages, or voltage drops during the last year. For the last five years, those with outage experience had several short outages, but very few of longer duration.

As reported in table 6.2 the average number of outages per year, the last 5 years, is 3.50, with a maximum of 10 outages. It can also be seen in table 6.2 that most outages are short, less than 5 minutes. Only one firm experienced an outage longer than four hours during the last five years. Five sites reported that they had caused power outages themselves during the last five years.

Of all the sites, about 70% (10 sites) had made a consequence analysis, or financial assessments, of outages. All but two of those reported that the analysis and assessment addressed the duration of an outage. Concerning action plans in case of an outage, about 90% of the sites answered that they have action plans. Those who reported no particular action plan answered that they have backup generators, or a way to adapt in production via some form of prioritized power supply. About 50% (7) of the sites answered that they have instructions for maintenance activities during outages, whereas 70% have instructions for alternative use of labor during outages, while about 40% have instructions of alternative labor use *after* outages.

Table 6.2. Supply reliability (outages), action plans and mitigation.

Outages	**Mean**	**Min**	**Max**
Number of outages per year last 5 years	3.50	0	10
less than 5 minutes	3.27	0	8
5-15 minutes	1.00	0	4
15-60 minutes	0.64	0	1
1-4 hours	0.09	0	1
> 4 hours	0.09	0	1
Action plans and measures			
Consequence analysis of outage (0 = no, 1 = yes)	0.69	0	1
Action plan for outage (0 = no, 1 = yes)	0.88	0	1
Cut-off time (before serious consequences)	8.07	0.17	24.00
Specific measures taken	0.75	0	1
Batteries installed	0.81	0	1
Generator installed	0.75	0	1
Batteries and generator installed	0.69	0	1

In some cases, it is reasonable to believe that there is a cut-off point in the duration of the outage where the consequences become very serious, and substantial actions must be taken. The respondents were asked if there is such a cut-off, and if so, when it occurs. The answers range from 0.17 hours (10 minutes) to 24 hours. The case of 10 minutes is in the foodstuff industry where machinery needs to be taken apart and cleaned already after 10 minutes. For other industries in foodstuff, it can be up to 24 hours. In other words, there is a large heterogeneity depending on the production process also within an industry/sector. In most cases however, the cutoff point for severe costs and problems in processes is in the range of hours with an average of 8 hours (see table 6.2).

As can be seen in table 6.2, a majority of sites have installed either batteries or generators, or both, as a backup. 81% have batteries, 75% generators, and 69% both. According to the comments made, the purpose with the battery and/or generator backup in most cases is to protect the most important functions (safety-critical fans and pumps, control systems, computer servers, etc.) in the processes and to protect sensitive equipment. For example, one company in the food industry answered that all control systems have UPS for 1 hour of operation. In three cases, the backup power also aims to maintain at least part of the production, protect input materials, and to avoid damages on machinery.

As is well-known from previous studies and experience, it is too simplistic to believe that the interruption in production processes corresponds exactly to the duration of the outage. Instead, the production delay will usually be longer than the outage itself. Among the responding sites, all but three reported that the production interruption becomes noticeable longer than the power outage itself. The other three reported that the production starts when the power is back. The latter was for the two firms in mechanical production industry, and for a milling company in foodstuff. Judging the link between the duration of outage and production interruption, most firms reported that a short outage corresponds to a short interruption in production. In all cases, the time to reach full production capacity was within 24 hours, except for three production sites (aluminum and petroleum). Two sites reported no extra costs to recover production. For those with extra costs, examples were overtime costs and costs for delivery delays.

The third part of the questionnaire contained explicit questions about costs for a one-hour outage, and what such cost consists of. Concerning the latter, it was explicitly asked about how to make an approximation of the costs associated with an hour of power outage. Three alternatives were given; sales value per hour; sales value minus reduced electricity and material cost; labor cost minus reduced electricity and material cost. As shown in table 6.3 a majority, 69%, states that the best approximation is the value of an hour of production. The rest also consider the reduced cost for energy and inputs, except one who suggested the cost for labor minus reduced energy and input costs, i.e. value added. The answer to the question if production losses resulting from a one-hour outage can be recovered within a year varies substantially between firms. Two firms state that it is very difficult to take back the production loss within a year, whereas four firms states that the possibility to take back losses are very good. The latter are firms within the food industry, whereas the former are very electricity intensive process industries.

Finally, in the third part of the questionnaire it was explicitly asked in monetary terms what the cost of a one-hour outage might be. As can be seen in table 6.3 the stated cost ranges between SEK 5000 and SEK 30 million, with an average of 3.4 million and a median of 0.4 million. Most of the variation is of course due to variation in firm size. Also, if we normalize with the production value per hour, we see that variation is large, between 0.19 and 42, with an average of 7 and a median of approximately 5. That the median is considerably lower reflects that there are a few very big firms, boosting the mean value. The latter figures can be interpreted as the share of an hourly production value. It means that the cost of an outage of one hour is equivalent to a five-hour (median) to seven-hour (mean) loss in production. Again, the highest values are found in energy intensive process industries like pulp and paper, petroleum, and metal industries. Compared to the estimates in the previous section, the costs reported in the questionnaire seems to be much higher

Table 6.3. Costs for a one-hour outage, thousand SEK.

	Mean	Median	Min	Max
Possibility to recover production within a year (1 = very bad, 5 very good)	3.06		1	5
What does the cost consist of?				
Sales value per hour (0 = no, 1 = yes)	0.69		0	1
Sales value minus reduced electricity and material cost (0 = no, 1 = yes)	0.19		0	1
Labor cost minus reduced electricity and material cost (0 = no, 1 = yes)	0.13		0	1
Cost for one hour outage, KSEK	3 441	400	5	30 000
Cost per employee, SEK	8 863	1000	154	100 000
Cost for one hour outage, share of hourly production value	7.23	4.82	0.19	42.30

One of the main objectives of the survey was to learn more about the potential heterogeneities within and across industries and sectors. Of course, the results are based on very few observations, but these observations may still point at important lessons to learn.

The questions focusing on the cost of a one-hour outage are of particular interest given the focus of the study. Several industries report that the cost to a large extent depends on what type of production process that they are in when the outage occurs. In one of the foodstuff sites, the cost is said to range from SEK 750 000 to 2 500 000 depending on what product they are producing. Some processes can start very quickly, while others may take 2-3 days to reach full capacity. They report that the situation becomes critical already after 10 minutes. The reason is that production equipment needs to be taken apart because of stuck “raw materials”.

In another food stuff related industry, the cost of one-hour outage is estimated to SEK 5 000 SEK. At this site, production is said to restart as soon as the power is back. Both large and small production losses can therefore be taken back without significant delays. Labor costs minus the reduced energy- and input costs is said to be a fair way to calculate the cost of a one-hour outage. As a reference, this site is relatively small with 30 employees and a yearly production value of SEK 220 million.

A pulp and paper site reports a cost of a one-hour outage to be about SEK 10 million. Our interpretation of their answers is that they come up with these numbers given that it takes about 24 hours to restart the production process to full capacity. Depending on where in the production process the outage occurs, the time to start up may differ. For example, if the outage affects water supply the start-up time will be relatively long in the pulp part of the process. As a reference, this site reports a yearly value of production to about 7 billion SEK, and that neither large or small production losses can be taken back within a year.

A steel industry reports a cost of a one-hour outage to be about SEK 10 million. It reports that an outage becomes critical in terms of e.g. extended interruption, sending home personnel, or initiating alternative duties after 7 hours. This is however said to depend on where in the production process the outage occurs. The interruption in production is also said to always be longer than the outage itself. Moreover, we interpret the responses from this site to reflect a worry for voltage dips. Answers indicate investments and actions taken in order to reduce risk of voltage drops and outages. As a reference, this site reports a yearly value of production to about SEK 7 billion. Finally, an approximation of costs by sales value is said to largely underestimate the true costs.

In a petroleum refinery, the cost of a one-hour outage is estimated to SEK 30-40 million. At this site, an outage becomes critical already after 10-30 minutes, with a typical restart time of about one week. They have been working on obtaining a more secure delivery of electricity from the grid owner, since they have problems with thunderstorms that causes several interruptions every summer season. The cut-off time for when a restart becomes problematic (with about one-week start-up time) is about 10 minutes. As a reference, this site stated a yearly production value of SEK 6 billion.

In summary, the questionnaire reveals that firms perceives that electricity supply is reliable. Quite few have experienced more than one outage per year the last five years. Furthermore, outages lasting longer than 15 minutes are extremely rare according to the survey. Another lesson learnt from the answers to the survey is that it seems difficult to give precise estimates of the outage costs, in spite of the attempt to reach out to the person in the company that are supposed to have the best knowledge. There are several reasons to this. One is that the consequences heavily depend on when the outage occur. For some firms it depends on the time of the day, whereas for others it depends on when in the process the outage occurs. The heterogeneity that is revealed by the answers is clearly reflected in the answer of how much they think an outage of one hour would cost. The range in the answer is considerable, irrespective of if we normalize it with production value or number of employees. For example, according to the answers the cost of a one-hour outage is between 0.19 and 42 hours of production, with a median of 5. In the upper range are firms in heavy process industries (petroleum, pulp and paper, steel), whereas firms in the lower range belongs to the sawmill industry and the food industry (except dairy industry). Whether this cost interval reflect real differences in costs, or if it just reflects different interpretations of the questions, cannot be said much about. A reasonable guess is that the interval reflects both. Although based on a very small sample the answers to the questionnaire, including the comments respondents gave, reveals the difficulties in estimating costs through a survey, and therefore one should be careful in drawing too strong conclusions from surveys. The results from the survey by Carlsson et al. (2019) tend to confirm this since 66% of the responded firms in their survey stated zero cost for a 3-minute outage, and 29% stated zero cost for a 12-hour outage. Both these numbers are remarkably high.

7 Summary and concluding remarks.

The objective of the present study is to complement previous literature on the cost of supply interruption, or outages, in Sweden by estimating the cost of power outages in the Swedish industrial sector using microeconomic (firm-level) production data.

The motivation behind the study is the ongoing transition of the power system featuring a high degree of intermittency at the same time as the transition in other sectors will require more electricity. Taken together this will make it more challenging to keep the instantaneous balance between demand and supply in the power market. If that balance is not secured, households and firms will most likely suffer from more interruptions in their use of power due to interruptions and power outages.

The main analytical approach taken here means that we departure from firms' actual behavior concerning their use of electricity and the values that this use creates. As such, this study differentiates from the bulk of previous studies that use stated preference data gathered through interviews and questionnaires. In addition, we contribute to previous studies by complementing the quantitative analysis with a more qualitative approach, where we use a questionnaire targeting key persons in a small number of industrial companies. The purposes with the survey study are to identify firm-specific aspects that that are not revealed by annual firm level data.

There is a quite extensive literature on the cost of electricity supply interruptions. For Sweden, such studies date back to 1969, which according to our knowledge is the first attempt to estimate interruption costs for different customer categories in Sweden, including the industry (see Andersson and Taylor, 1986). The 1969 study was followed up by a similar study in 1980, which revealed that the cost per unit of lost load had increased 3 times during the 10 years between the studies. More recent studies (Carlsson and Martinsson, 2006, Carlsson, et al., 2019) points in the same direction. Taken together this indicates that the industry has become more vulnerable to supply interruptions over time. Common for all previous Swedish studies is that the cost estimates are based on questionnaires to the companies, where it is asked directly what the cost is for supply interruptions of different durations. Somewhat surprising from the more recent studies is that a large share of the respondents answers zero cost. In the most recent study, Carlsson et al. (2019), 66% of the responding companies state zero cost for a 3-minute outage, and 29% state zero cost for a 12-hour outage. This may indicate that surveys in which companies are asked to state their cost should be interpreted with care. According to the results from the (small) survey made in this study no firm state zero cost. On the contrary most firms state relatively high costs, up to 42 hours of production loss for a one hour outage.

The most common measure of the interruption cost is the value per unit of electricity that is not delivered, the *value of lost load*, VoLL. It is simply calculated as the cost divided by the actual use of electricity, hence giving a value per KWh. VoLL is useful if, for example, an electricity shortage happens. In this case some users may have to be disconnected. The total costs of an interruption can then be minimized by disconnecting the users with the lowest VoLL. However, a property with VoLL is that the implied duration of the interruption will differ between firms and sectors, which causes a problem if we want to make cost comparisons for an interruption with a given duration. This in turn implies that is not straightforward to use VoLL in a benefit-cost assessment of potential measures to mitigate the risk of an interruption of a specific duration. In such case a cost per unit of duration, *cost per hour* (CpH), may be more useful.

Here we have calculated what we call upper and lower limits for both VoLL and CpH. The lower limit corresponds to the case when both labor and material input is completely flexible in the sense that labor can be dismissed, and material can be stored without any losses, and the upper limit corresponds to the case when labor cannot be dismissed, but material can be stored for future use. The upper value equals then loss in profit and labor cost (value added or compensation to primary factors of production).

Compared to other studies, the VoLL estimates here are in the same range as the estimated VoLL for Ireland, found in Leahy and Tol (2011), and slightly higher than the value found in de Nooij et al. (2007) for the Netherlands. This reflects that the Swedish industry generates about the same value added per unit of electricity as the Irish industry, but slightly more than the industry in the Netherlands. Comparing the estimated cost per hour (CpH) with the estimates in Carlsson et al. (2019) reveals a significant difference when it comes to industry-average. The industry-average estimate in Carlsson et al. is about 4 times the value found here. Interestingly, however, is that the median is almost the same in our study and in Carlsson et al. There are several possible explanations to the differences and similarities. One reason is that the estimate in Carlsson et al. is based on stated preferences, whereas we in this study use revealed preferences (actual behavior). This may at least partially explain the higher average value in Carlsson et al. since the stated preference approach may be subject to so called hypothetical bias but may also capture costs that are not directly related to the production loss in the particular hour when the outage occur. Another possible reason to the difference between the estimated average cost may be due to the sample used in Carlsson et al. In this study in principle all manufacturing firms are included, whereas Carlsson et al. base their analysis on a sample of 750 firms, with a clear overrepresentation of large firms. This may also explain part of the difference between the average values, and the similarity with the median.

To summarize, the main conclusion from this study is that the costs for the industry of supply interruptions are considerable, and seems to have increased over time, suggesting that the industry have become more vulnerable to supply disturbances. In 2016 the estimated cost of a one-hour outage for an average industrial facility in Sweden was approximately 23 times larger than the value of the electricity not delivered (SEK 9502 versus SEK 400), whereas the cost in 2004 was approximately 13 times the market value of the electricity not delivered. However, there is substantial variation across firms and sectors. For an average facility in the electro and motor vehicle industry, for example, a one-hour cost is, according to our estimates, about 120 and 105 times the market value of the electricity not delivered, respectively (SEK 43680 versus SEK 415 for an average motor vehicle firm). In the pulp and paper industry, on the other hand, the outage cost is only about 5 times the value of undelivered electricity in spite of a relatively high outage cost in absolute value (SEK 27730). The reason for the relative low ratio for the pulp and paper industry is that they are very electricity intensive.

The numbers above can now be used to calculate the cost of, say, an increased risk for an outage, or the willingness to pay for avoiding that risk (for the latter, see discussion in Appendix A). Suppose, for example, that we have fully reliable electricity supply with zero outages, but that the risk for an outage increases (for some reason). As an example, suppose that the probability for one one-hour outage for an average firm goes from zero to 0.1 (10% of the facilities in Swedish industry are expected to have one one-hour outage during a year from now on). Given the estimates in this study the expected annual cost equals SEK 9502 multiplied by ten percent of the firms, which equals 3.9 million SEK. Assuming a discount rate of 3% the present value amounts to 130 million SEK (infinite time horizon). The corresponding electricity that is not delivered is 330 MWh, which have a market value of approximately 0.16 million SEK annually (assuming that the electricity price is SEK 500 per MWh) and thus a present value of 5.5 million SEK (3% discount rate, infinite time horizon). Clearly, the willingness to pay to avoid the risk exceeds the market value of the undelivered electricity. To avoid the risk firms would, according to the results, be willing to pay a maximum price of almost 12 thousand SEK per MWh for the undelivered electricity (more than 20 times the current price).

It should be stressed that these numbers should be interpreted with care since they assume that the interruption in production processes corresponds exactly to the duration of the outage, but also that the production losses during the outage are lost forever and cannot be compensated for in any way. However, according to the results from our survey a majority of firms reported that the production interruption becomes noticeable longer than the power outage itself. In addition, most firms reported additional costs because of an outage, such as costs for overtime and delivery delays. On the other hand, several firms reported that they may be able to "take back" the production losses during a year. Taken together, however, the first effects seem to dominate, according to the survey results. This means that the cost estimates reported above should be interpreted as lower bounds.

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Appendix A:

VoLL and certainty equivalence - a theoretical value of hedging against lost load of electricity.

Being faced with the uncertainty of potential lost load will give the firm incentive to incur cost to try to hedge against this undesirable outcome. This note explores the possibility to theoretically assess the value of hedging against lost load using the concept of certainty equivalence.

Assume a firm that use, among other inputs (X), electricity (E) to produce output (Q). Write the production function as

$$Q = Q(X, E)$$

Profits can then be expressed as

$$\pi = \pi\big(Q(X, E)\big) = \pi(X, E)$$
$$\frac{\partial \pi}{\partial E} > 0, \frac{\partial \pi^2}{\partial^2 E} < 0$$

Assume now that the probability of a business-as-usual (BAU) outcome in a specific period is p and the probability of lost load or outage is (1 - p). The value/cost of electricity used associated with the outcome p is E^*, and the value of electricity use associated with (1 - p) is 0. If lost load occurs production stops and the loss for that period is C (start-up costs, loss of profit/output, etc.)

Expected value/cost of electricity use in each period with the risk of lost load becomes

$$Exp[E] = pE^* + (1 - p) \cdot 0 = pE^*$$

Expected profits in each period with the risk of lost load becomes

$$Exp[\pi(X, E^*)] = p\pi(X, E^*) + (1 - p)\pi(X, 0) = p\pi(X, E^*) - (1 - p)C$$

What would be the amount or value of certain electricity delivery that the firm would accept if it could hedge away the uncertainty? That would be the amount of electricity (E^{CE}) that makes expected profits equal to the certainty equivalent level of profits, that is,

$$Exp[\pi(X, E)] = \pi(X, E^{CE})$$

or

$$p\pi(X, E^*) - (1 - p)C = \pi(X, E^{CE})$$

Assuming $\pi(X, E) = \pi(E) = \sqrt{E}$ (suppressing X) for BAU, and $\pi(0) = -C$ for when an outage occurs, we can write

$$p\sqrt{E^*} - (1 - p)C = \sqrt{E^{CE}}$$

So that,

$$E^{CE} = p^2 E^* - (1 - p)^2 C^2$$

Now observe the Illustration presented below. The distance between the expected value of electricity pE* and ECE is the amount of electricity that the firm would willingly forego to achieve a certain amount of electricity instead of the expected or amount which is associated with the "gamble" that the positive probability of lost load introduces. The profit foregone, or willingness to pay for the no-risk outcome, is the difference between profits at the "gamble" electricity level pE* and profits at the certainty equivalence use of electricity ECE. That is, lost value of eliminating risk (LVER) is

$$LVER = \pi(pE^*) - \pi(E^{CE}) > 0 \ ,$$

if the profit function is concave in E. In other words, the loss in profits that the firm is willing to accept (WTA) to eliminate the risk of lost load. Using $\pi = \sqrt{E}$ we can write this expression as

$$LVER = \sqrt{pE^*} - \sqrt{p^2E^* - (1-p)^2C^2}$$

The effect of increasing the probability of the bad outcome (decreasing p) is that the cost of eliminating risk, *LVER*, increases (that is, $dLVER/dp < 0$, meaning $dLVER/d(1-p) > 0$.

In sum; the firm would be willing to incur costs (or lose profits) in order to avoid the risk of lost load and that cost is associated the probability of an unfavorable outcome, p, the level of the desired outcome electricity, E^*, and the cost of an outage, C. The more firms dislike risk, the larger the WTA a profit loss to achieve a certain outcome, as is represented by the curvature or concavity of the profit function, $\pi(E)$.

The figure below summarizes the argument. The concave curvature of the profit function signals risk-aversion. This risk-aversion induces a value of a certainty equivalence outcome, that is, the WTA a loss in profits to avoid the gamble of potential lost load. The more concave

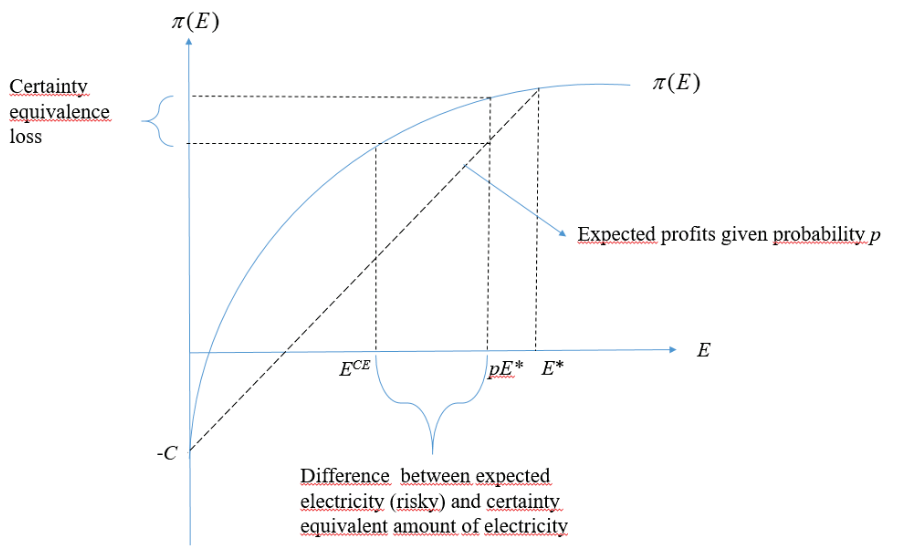

Illustration: Certainty equivalence loss when profit function is concave in electricity use.

the profit function, the more risk-avert the firm is, and consequently the higher the WTA value for a certain outcome.

Numerical example:

- Let's assume the desirable outcome is E^* = 100.
- Further, assume that the probability of lost load is (1 - p) = 0.1, that means the probability of a desirable outcome is p = 0.9.
- The loss incurred by lost load (when E = 0) is C = 5.
- The profit function is $\pi = \sqrt{E}$

With these assumptions we can calculate the expected level of electricity (i) pE^*, (ii) the expected profits with uncertainty $Exp\left[\pi(E)\right]$, (iii) the certainty equivalent level of electricity E^{CE} and the associated profits, and (iv) the profits foregone to eliminate the risk of lost load, that is, *LVER*.

First, the expected amount of electricity in BAU scenario is:

pE^* = 0.9(100) = **90**

Expected profits are given by:

$$Exp[\pi(E)] = p\pi(E^*) - (1-p)C = 0.9\sqrt{100} - 0.1(5) = \mathbf{8.5}$$

The certainty equivalent energy level is given by:

$$E^{CE} = p^2E^* - (1-p)^2C^2 = 0.9^2(100) - 0.1^2 5^2 = \mathbf{80.75},$$

which is 9.25 units lower than the expected or "gamble" level of electricity. This will define the WTA for this firm; see Certainty equivalence loss in figure above.

The (lost) value of eliminating risk is given by:

$$LVER = \sqrt{pE^*} - \sqrt{p^2E^* - (1-p)^2C^2} \approx \mathbf{0.5}\ ,$$

which is the loss in profits or cost of the risk-free alternative (certainty loss in Illustration above) and amounts to about 6% of expected profits. An increase in the probability of an outage will increase the WTP for the certain outcome, that is, *LVER* goes up.

Appendix B:

Mean, median, lower, and upper quartiles of VoLL and CpH 2004, 2008, 2012 and 2016.

Table B1. Mean, median, lower (p25) and upper (p75) quartiles of VoLL in 2004, SEK/KWh.

	VoLL(H)				VoLL(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	17.58	6.26	3.23	13.23	4.89	0.38	0.03	1.77
Chemical	31.91	17.06	5.86	31.97	6.46	1.19	0.09	4.59
Electro	130.91	86.05	43.90	173.72	11.33	5.10	0.28	18.28
Fabricated metal	32.95	18.77	10.43	32.21	2.21	0.61	0.01	2.37
Food	23.90	13.06	7.54	20.71	10.36	0.49	0.00	1.51
Machinery	54.45	29.84	17.47	52.73	6.33	1.46	0.03	5.48
Mining	44.57	11.57	4.03	53.95	2.81	0.76	0.24	5.60
Motor vehicles	38.24	22.89	14.06	37.35	3.44	1.05	0.05	3.71
Printing	64.92	28.33	17.40	64.78	4.07	0.80	0.00	3.65
Pulp & paper	22.74	13.30	2.23	25.13	2.61	0.20	0.00	1.72
Rubber & plastic	26.78	10.68	5.41	23.21	2.85	0.52	0.00	2.02
Stone & mineral	49.22	14.52	7.04	41.26	4.61	0.85	0.00	3.05
Textile	44.70	24.41	12.84	47.68	3.77	0.99	0.09	4.15
Wood	21.02	10.33	4.34	21.88	1.45	0.35	0.01	1.34
Industry	46.34	20.65	10.13	41.97	4.91	0.80	0.01	3.50

Table B2. Mean, median, lower (p25) and upper (p75) of CpH in 2004, SEK.

	CpH(H)				CpH(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	14909	2312	858	7401	4260	120	15	857
Chemical	22257	2567	921	8528	7251	192	9	1438
Electro	9378	2369	1186	5688	824	135	4	540
Fabricated metal	1965	907	527	1779	218	30	1	133
Food	6526	1128	511	3100	3287	36	0	231
Machinery	4939	1365	725	3618	1005	65	2	312
Mining	17456	1466	1136	4280	5294	99	21	499
Motor vehicles	29455	2666	1215	7470	6189	130	5	490
Printing	2894	1236	653	3035	189	24	0	166
Pulp & paper	21144	3506	1061	18447	3732	97	0	770
Rubber & plastic	2737	1283	660	2834	252	63	0	211
Stone & mineral	6141	1551	759	5353	620	53	0	405
Textile	2631	1069	557	1971	273	45	2	177
Wood	2791	1178	607	2699	170	43	1	159
Industry	6756	1303	666	3378	1427	51	1	262

Table B3. Mean, median, lower (p25) and upper (p75) of VoLL in 2008, SEK/KWh.

	VoLL(H)				VoLL(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	31.94	12.64	6.49	31.64	3.66	0.88	0.00	3.73
Chemical	37.24	20.45	8.72	41.15	6.81	1.08	0.00	5.53
Electro	126.45	91.77	46.59	149.43	14.15	5.61	0.38	20.05
Fabricated metal	46.61	28.24	16.30	49.76	4.85	1.61	0.17	5.09
Food	25.83	15.49	9.96	26.42	0.58	0.36	-0.04	1.89
Machinery	67.37	42.25	23.75	73.27	7.77	2.98	0.39	9.35
Mining	109.78	39.00	8.73	111.70	-6.64	2.32	0.31	11.71
Motor vehicles	44.92	28.15	15.75	50.65	3.85	1.08	-0.26	4.50
Printing	46.40	26.23	16.92	43.92	2.09	0.50	0.00	2.49
Pulp & paper	24.36	14.07	2.74	31.98	2.42	0.18	-0.07	2.11
Rubber & plastic	28.37	14.72	7.16	34.07	2.69	0.75	0.00	3.52
Stone & mineral	65.68	29.07	13.85	61.64	7.24	1.83	0.03	7.41
Textile	55.41	36.92	19.59	66.06	6.25	1.31	0.01	6.17
Wood	33.48	17.36	6.95	43.10	2.24	0.67	0.00	3.18
Industry	51.24	27.12	13.67	55.29	4.93	1.33	0.02	5.26

Table B4. Mean, median, lower (p25) and upper (p75) of CpH in 2008, SEK.

	CpH(H)				CpL(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	20126	3743	1116	8777	2707	136	0	952
Chemical	13245	3530	1488	10407	2600	138	0	1105
Electro	6297	2518	1278	5527	-99	174	8	648
Fabricated metal	2543	1182	762	2254	437	70	9	216
Food	6562	1096	566	2816	612	24	-2	155
Machinery	7918	1920	920	4976	1319	115	16	470
Mining	32564	2049	1389	4667	10138	249	41	628
Motor vehicles	23900	2867	1356	6846	1980	74	-60	447
Printing	2673	1187	689	2448	101	20	0	120
Pulp & paper	20064	2673	1169	14991	5459	59	-58	498
Rubber & plastic	3275	1506	825	3180	305	78	0	288
Stone & mineral	7130	1832	845	6152	1516	97	3	510
Textile	2462	1103	597	2263	228	40	1	177
Wood	3159	1324	825	2721	88	50	0	242
Industry	6740	1521	814	3665	947	70	1	318

Table B5. Mean, median, lower (p25) and upper (p75) of VoLL in 2012, SEK/KWh.

	VoLL(H)				VoLL(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	33.75	13.20	5.59	33.88	1.38	0.11	-0.28	2.51
Chemical	46.35	26.25	10.98	50.39	6.70	1.18	0.00	5.25
Electro	121.49	81.69	42.21	161.64	12.69	4.83	0.22	16.95
Fabricated metal	50.01	29.64	17.79	55.74	3.90	1.11	0.04	4.48
Food	33.38	19.98	11.80	35.64	2.06	0.56	0.00	2.55
Machinery	69.85	45.07	25.43	83.14	8.10	2.34	0.01	9.09
Mining	113.43	35.17	13.06	126.43	9.51	4.38	1.04	15.45
Motor vehicles	50.79	32.69	16.61	57.19	3.36	0.86	-0.96	5.73
Printing	56.35	29.60	19.63	50.88	3.69	1.14	0.01	4.08
Pulp & paper	26.87	14.70	2.47	31.09	3.32	0.09	-0.05	2.02
Rubber & plastic	33.69	16.45	8.54	38.99	2.54	0.75	0.03	3.15
Stone & mineral	63.45	34.86	15.15	73.15	6.64	1.90	0.01	7.61
Textile	64.36	39.70	16.53	87.34	3.75	1.04	0.02	5.03
Wood	36.79	18.57	6.84	45.68	2.11	0.18	-0.25	2.25
Industry	54.29	29.44	14.83	60.26	4.77	1.03	0.00	5.01

Table B6. Mean, median, lower (p25) and upper (p75) of CpH in 2012, SEK.

	CpH(H)				CpH(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	13485	3423	1451	8059	-1972	16	-137	337
Chemical	18690	4373	1373	11618	4411	182	0	1427
Electro	5356	2238	1132	4521	797	152	3	545
Fabricated metal	2642	1266	792	2408	310	50	2	197
Food	7217	1297	663	3265	1350	27	0	185
Machinery	9450	1925	1016	4849	1818	86	1	423
Mining	49206	2094	1373	4704	18722	278	44	988
Motor vehicles	24664	2920	1604	5982	3637	69	-140	357
Printing	2996	1385	885	2874	201	49	0	182
Pulp & paper	21517	3754	1286	15505	2820	59	-12	567
Rubber & plastic	3774	1698	910	3562	252	73	2	302
Stone & mineral	7729	2102	955	5580	1087	91	2	430
Textile	2327	1174	652	2142	147	49	0	124
Wood	3183	1305	750	2732	-77	13	-38	114
Industry	7346	1631	872	3804	1130	54	0	268

Table B7. Mean, median, lower (p25) and upper (p75) of VoLL in 2016, SEK/KWh.

	VoLL(H)				VoLL(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	41.59	11.92	6.02	28.83	4.46	0.26	-0.06	2.35
Chemical	55.30	31.05	15.10	56.82	3.68	2.09	0.10	6.98
Electro	155.69	101.30	50.49	199.34	16.51	5.91	0.44	21.53
Fabricated metal	59.50	33.71	18.90	66.31	5.30	1.23	0.04	5.15
Food	38.03	24.14	13.26	43.31	2.50	0.94	0.01	3.57
Machinery	96.30	56.59	31.33	107.79	12.06	2.98	0.09	11.96
Mining	118.19	47.97	15.04	142.77	29.05	6.44	1.10	25.33
Motor vehicles	61.66	39.25	21.79	66.71	5.93	1.57	0.02	7.90
Printing	63.80	30.89	21.57	54.41	4.60	1.05	0.01	3.62
Pulp & paper	29.13	18.05	4.53	35.92	2.29	0.09	-0.03	1.39
Rubber & plastic	45.18	21.80	9.78	51.66	6.12	1.26	0.09	4.91
Stone & mineral	83.68	44.24	22.01	86.28	7.22	1.96	0.09	9.29
Textile	74.61	44.82	19.49	98.76	8.67	2.73	0.29	9.56
Wood	54.25	26.48	9.14	58.65	6.89	1.40	0.12	5.12
Industry	*68.76*	*35.76*	*17.86*	*75.51*	*7.19*	*1.54*	*0.03*	*6.67*

Table B8. Mean, median, lower (p25) and upper (p75) of CpH in 2016, SEK.

	CpH(H)				CpH(L)			
	Mean	Median	p25	p75	Mean	Median	p25	p75
Basic iron & steel	17141	2890	1156	7408	925	54	-32	553
Chemical	23066	5265	1483	16395	90	252	24	1312
Electro	6780	2531	1287	5670	818	185	9	678
Fabricated metal	3097	1446	903	2863	274	63	2	222
Food	9090	1469	729	4607	739	59	1	316
Machinery	10469	2472	1274	6778	930	140	4	616
Mining	51224	2872	1831	6471	5437	445	98	1136
Motor vehicles	43681	3428	1549	7913	4179	137	1	552
Printing	2995	1412	790	3046	124	38	0	167
Pulp & paper	27730	4887	2014	22553	-330	64	-5	386
Rubber & plastic	4609	2056	1132	4682	502	133	13	383
Stone & mineral	9701	2909	1149	6894	1564	157	12	626
Textile	3743	1333	843	2543	407	107	10	232
Wood	5119	1802	960	4358	448	110	9	390
Industry	*9502*	*1935*	*1019*	*4822*	*733*	*95*	*2*	*380*

Table B9. Mean, median, lower (p25) and upper (p75) of CpH per employee in 2016.

	Mean	Median	p25	p75
Basic iron & steel	85	76	55	101
Chemical	136	100	74	163
Electro	98	84	65	114
Fabricated metal	76	69	57	87
Food	78	62	45	89
Machinery	96	83	64	110
Mining	158	141	106	196
Motor vehicles	85	75	64	92
Printing	71	66	55	83
Pulp & paper	106	84	70	127
Rubber & plastic	87	78	64	102
Stone & mineral	100	82	63	114
Textile	74	65	55	80
Wood	82	74	58	99
Industry	87	74	59	99

THE VALUE OF LOST LOAD IN SWEDISH INDUSTRY

The main conclusion from this study is that the costs for the industry of supply interruptions are considerable, and seems to have increased over time, suggesting that the industry have become more vulnerable to supply disturbances.

In 2016 the estimated cost of a one-hour outage for an average industrial facility in Sweden was approximately 23 times larger than the value of the electricity not delivered (SEK 9502 versus SEK 400), whereas the cost in 2004 was approximately 13 times the market value of the electricity not delivered.

These numbers should be interpreted with care since they assume that the interruption in production processes corresponds exactly to the duration of the outage, but also that the production losses during the outage are lost forever and cannot be compensated for in any way. The estimates complements previous studies based on stated preferences, and can be used practically in benefit-cost assessments of potential measures to mitigate risks of electricity supply interruptions.

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