

# Rapporto tecnico N.52



**Benefit analysis. Assessing the cost of blackouts  
in case of attack. Evaluation based on Italian  
and Polish case studies.**

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## RAPPORTO TECNICO CNR-CERIS

Anno 9, N° 52; Ottobre 2014

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## *ESSENCE*

*Emerging Security Standards to the EU power Network controls and other Critical Equipment*

*A project financed under the programme "Prevention, preparedness and consequence management of terrorism and other security-related risks" HOME/2011/CIPS/AG*

The Essence project is a study to evaluate costs and benefits of the implementation of security standards to critical electric infrastructure, based on two case studies.

Networked computers reside at the heart of critical infrastructures, these are vulnerable to cyber attacks that can inhibit their operation, corrupt valuable data, and expose private information. Such attacks might affect large portions of the European power system, make repair difficult and cause huge societal impact, so that pressure to ensure cyber security of control and communication systems is now very strong worldwide. To that aim, several frameworks have been developed or are under development at present, both in the form of guidelines and proper standards, but it is difficult to evaluate costs and benefits of their adoption, although experimentation so far has shown that they may be huge.

In this scenario the key objectives of ESSENCE include:

1. Developing a common understanding of industrial needs and requirements regarding the security of control systems and the related standardisation efforts;
2. Identifying power system vulnerabilities induced by control systems, and estimating the likely socio-economic impact of failures due to faults and attacks exploiting those vulnerabilities;
3. Evaluating emerging frameworks for ensuring industrial control systems security, and establishing the costs of their adoption on an objective basis;
4. Recommending a pathway towards adoption of one or more of the above frameworks to the European power system infrastructure, having specific regard to EU transnational infrastructures as defined by the Directive 2008/114/EC.

The results of the study will be published in a series of technical reports, hosted in the "Ceris Technical reports series". The published titles are:

1. Considerations on the implementation of SCADA standards on critical infrastructures of power grids
2. Attack scenarios. Threats, vulnerabilities, and attack scenarios along with their selection criteria

# Benefit analysis. Assessing the cost of blackouts in case of attack. Evaluation based on Italian and Polish case studies.

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**ABSTRACT:** This report provides an economic quantification of the benefits of implementing security standards, expressed in terms of avoided costs of blackouts. The evaluation considers specifically the blackouts described in the Italian and Polish trials, employing a mixed methodology relying on the “production function” approach for the non-household sector, while an econometric method based on survey data (stated preferences) is used for household consumers. With reference to non-households, a separate evaluation is carried on for the electricity industry. The results show that the costs of blackout are substantial, either for household and non-household consumers, and largely exceed the damage suffered by the utilities due to lost sales. Finally, since for non-households only losses in production are considered, we provide, in a separate section, three case studies demonstrating that some industries can suffer relevant additional blackout costs.

**Keywords:** Cost of blackouts, production function, choice experiment, willingness-to-accept

**JEL code:** D12; D61; L94

## SUMMARY

1. Introduction: benefits analysis as avoided costs of blackouts .....	7
2. Evaluating the cost of blackouts: literature review.....	9
2.1 Methodologies overview .....	9
2.2 Studies employing the “Production function” method .....	10
2.3 Survey-based studies .....	11
2.4 Studies based on market behavior analysis and case-studies .....	14
3. Empirical application.....	18
3.1 Choice of methodology. ....	18
3.2 Non-household consumers: “production function” approach.....	18
3.2.1 Application to the Italian trial.....	20
3.2.1.1 Global damage to the productive system.....	20
3.2.1.2 Damage to the electricity sector .....	23
3.2.2 Application to the Polish trial.....	25
3.2.2.1 Global damage to the productive system.....	25
3.2.2.2 Damage to the electricity sector .....	27
3.3 Household consumers: survey-based methodology.....	29
3.3.1 Willingness to pay vs Willingness to accept .....	29
3.3.2 The questionnaire .....	30
3.3.3 Data.....	31
3.3.4 Model.....	34
4. The cost of blackout for individual firms: case studies .....	39
4.1 Isolpack SpA .....	39
4.2 Cement producer .....	42
4.3 Milk producer .....	44
5. Conclusions .....	45
References .....	47

## 1. INTRODUCTION: BENEFITS ANALYSIS AS AVOIDED COSTS OF BLACKOUTS

The Essence project wants to assess the impact of the implementation of some standard countermeasures against attacks of cyber-terrorists. Two case-studies, based on an Italian generator and on a Polish TSO, have shown that some threats, properly addressing some vulnerabilities of the two systems, could turn in large and extended blackouts. The aim of this report is to give an assessment of the damage caused by these two hypothetical – but very precisely defined – blackouts, which could be avoided thanks to the implementation of proper standards.

Electricity supply security is a very important feature of the whole electric service. Over time, most human activities in developed countries have become more and more dependent on the stable presence of electric energy. This is true not only for productive sectors (industry and services), but also for most part of the every-day home activities, such as housework, cooking, or leisure activities: watching TV, surfing on the internet, and also reading, at least in the evening.

In most developed countries, the service reliability has reached very high levels, so that an outage is often considered as an exceptional event. For this reason, when it happens (especially if it is unexpected), it creates huge inconveniences (see the following literature review in section 2 for some examples of quantification).

Although consumers would surely agree that electricity supply security has a relevant value, how high this value is (in monetary terms) represents a very difficult question.

The main difficulties to the evaluation are linked to the fact that supply security is a non-tradable public good (see Garcia et al., 2013). Public goods have the common properties of being non-rival and non-exclusive in consumption. Non-rivalry implies that consumption of that good by one person does not limit its use by other people. Non-exclusivity indicates that individuals cannot be excluded from consumption. In general, public goods are also non-tradable, i.e. it does not exist any market where they can be sold or purchased. This implies that no price is available for them. This is the main point that complicates the economic evaluation: the value of a good is often reflected in its market price. Since there is no market price for supply security, its value must be inferred in a different way.

Since direct measurements of the value of service reliability are in general considered as very difficult tasks, a reasonable and broadly accepted approach to evaluate supply security is estimating the damage that would occur in case of failure (Ghajar and Billinton, 2006). Failures can assume different forms, such as blackouts (loss of power lasting a period of time), brownouts (non-complete drop in voltage), transient faults (loss of power lasting few seconds), etc. In this study, we concentrate on the consequence of blackouts in selected areas, since this is the kind of failure considered in the Italian and Polish trials developed within the ESSENCE project.

Blackouts can generate different kinds of damage; following Billinton et al. (2001) it is relevant to distinguish between economic and non-economic (social) costs; moreover, some damage categories present an evident causal relationship with the interruption, while in other cases this link is weaker.

Among the immediate effects of the cessation of supply, the main drawback for the productive sectors is lost production. However, depending on the production process characteristics, also other categories of damage can be relevant. This is the case of idle or spoiled production factors (labour, materials, capital), damaged equipment, re-starting costs. For households, spoilage of food is one annoying inconvenience. All these

sources of damage can be classified as “economic”, since they generate a monetary (“out-of-pocket”) loss, or a reduction in profit.

Anyway, other sources of inconvenience play important roles, though they do not generate monetary losses: these can be classified as “social” costs of interruptions and involve the loss of leisure time, the inconvenience due to the lack of services, uncomfortable temperature in buildings, mental stress, etc. It is clear that these costs apply to individuals, while firms mainly face purely “economic” damages.

Finally, other costs arise as mediate consequences of the interruptions, such as the increase in criminal activity, and their evaluation is even more complex.

This work focuses on the damage generated by interruptions, considering both economic and social costs. However, developing a methodology including *all* the possible sources of damage is not a feasible exercise. For reasons that will be illustrated subsequently, we have decided to focus on some costs categories.

- For individuals we have adopted a survey-based methodology aimed to evaluate the *whole* damage suffered by a household during a blackout. Therefore, both economic and social costs are included in the analysis, with reference to the domestic life of individuals.
- For firms, we evaluate the damage in terms of lost production.

Other kinds of damage can play a relevant role, but are not included in the quantitative analysis as a consequence of the chosen approach. This is the case of damage to equipment and plants, losses in raw materials and long re-starting times for firms. Section 4 of this work tries to fill this gap providing a qualitative analysis focused on single firms in the form of case-studies.

Moreover, social costs do not involve only the domestic life of individuals, but are also related to the availability of essential collective services such as public health, transports, or communications. These costs as well have not been included in the quantitative analysis which, for this reason must be considered of a sort of “lower bound” or prudent estimate.

## 2. EVALUATING THE COST OF BLACKOUTS: LITERATURE REVIEW

### 2.1 Methodologies overview

Blackout cost evaluation is a complex issue. The main difficulty relies to the fact that, although markets for electricity exists, markets for interruptions do not, therefore it is not possible to rely on market prices to estimate the economic value of electric supply continuity.

Nevertheless, in the economic literature several methods have been developed to infer the cost of electricity interruptions. De Nooij et al. (2007) provide a taxonomy.

- *Stated preferences methods*, based on surveys. Interviewed people are asked to state a value for blackouts. Initially the idea was just to ask the interviewees to quantify the cost or the inconvenience linked to outages. More recent approaches are aimed to elicit the value respondents assign to supply continuity either in terms of amount they would pay to avoid or reduce the interruption (willingness to pay - WTP) or in terms of amount they would like to receive as a compensation for an increase in interruptions (willingness to accept – WTA). They can also be asked to choose among given combinations of interruption characteristics and monetary values. This method is useful since it relies on preferences directly elicited from the interviewees. The main drawback is related to the fact that this approach can be prone to different types of bias of cognitive source; in particular, the way questions are asked plays a major role.
- *Production function approach*, which estimates the damages from interruptions in terms of lost production (non-households) or lost leisure time (households). The damage is proportionally related to the energy lost, since the underlying assumption is that no productive activity is possible in absence of electricity (in the same vein, leisure time cannot be enjoyed in case of electricity interruptions). The main advantage is that the application is straightforward once macro-economic data on production and energy consumption are publicly available. The main drawbacks rely on the fact that the result is an approximation of the total damage (some authors identify this category as belonging to the *proxy methods* class), as it ignores factors such as restarting times, damages to equipment or non-complete energy dependence. Nevertheless, most authors agree in recognizing that these approaches provide a good estimate of the order of magnitude of the global damage, although they are often judged not suitable when precise information is needed for detailed system planning. More advanced applications, requiring a broader set of information, rely on input-output matrices to consider the interdependence across different sectors or on methods assigning a positive cost for load disconnected in addition to the cost for energy non-supplied.
- *Revealed preference methods*, based on market behaviour. These methods infer the value of supply security by observing some particular choices of electricity users, such as the purchase of backup facilities or the use of interruptible contract. This approach has the appealing feature of relying on real market choices. On the other hand, these choice options are available for few users categories (mainly large users), while no information would be provided with respect to the other segments.
- *Case studies*. The common feature of this set of approaches is the presence of a real blackout. The consequences of the blackout can be listed and monetized, or a survey can be carried out immediately after the event. The main desirable property of this method is that it allows to evaluate the consequences of a real event, or at least that the temporal proximity of a real event increases the

consumers awareness about the actual value of the service. However, the possibility of generalizing or extending the evaluation to other events is limited.

Finally, the different approaches are not mutually exclusive: Reichl et al. (2013a, b) employ the stated preference approach for households and a method based on the production function enriched with information collected through firms survey for the productive sectors.

The empirical evaluation of the cost of blackouts has been a debated issue in economics at least for the last four decades.

An excellent review of the early works on this topic is provided by Caves et al. (1990). The authors highlight the relevant variability of results remarked in the literature, which depends on the underlying methodologies, but also on the reporting procedures and on whether (and which) users and blackout characteristics are considered. The authors report, from the reviewed literature, that the outage costs for residential users range from 0.04 to 31.5 \$/kWh<sup>1</sup>. For industry the values are between 2.74 and 48.42 \$/kWh with proxy methods providing lower results with respect to surveys. Finally, for the commercials the range is between 10.82 and 46.85 \$/kWh.

Such a variability of results continues to characterize the research in this field. The following subsections will present an overview of some among the recent works on this topic. The review, far from being exhaustive of the broad existing literature, is mainly aimed at providing examples of the variety of approaches implemented and on the variability of results obtained, as a further evidence of the complexity of the issue we are going to treat. Moreover, we believe it is very interesting to notice that, over time, residential users damage evaluation has lost its marginal role, becoming the main focus of many among the most recent studies.

## 2.2 Studies employing the “Production function” method

Although the approach based on the ratio “GDP/energy consumption” has been one among the first methods employed for measuring the cost of blackouts, some recent contributions have provided refined versions of that, able to differentiate the damage across sectors and to provide an evaluation for households. Below we will provide some examples.

De Nooij et al. (2007) apply the production function method to evaluate the cost of blackouts in the Netherland, with reference to the whole country. The damage for firms is expressed in terms of lost production (i.e. lost value added) per kWh of energy non-delivered, or per hour of interruption. The damage incurred by households is evaluated as non-enjoyed leisure time, whose monetary value is assumed to be equal to the net income per hour for working people (halved for non-working people). The results show an average VOLL (value of lost load) of 10.89 €/kWh over the whole country, with the unitary cost for households largely exceeding the corresponding value for non-households (firms and governments): 20.84 €/kWh vs 7.59 €/kWh. They also find that 1-hour interruption generates a damage of 3.40 € per person, reduced to 3.03 € if the interruption happens in a weekday, during the day. Overall, a 1-hour interruption is estimated to cost, to the whole country (weekday) about 202 € millions during the daytime and 128 € millions in the evening.

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<sup>1</sup> All monetary values in this chapter are adjusted for inflation to the first quarter 2014

The findings of this study have been later employed in De Nooij et al. (2009), where the VOLL measure was derived for the municipal level, in order to suggest an efficient rationing strategy in case of power supply shortage, based on local VOLL.

Also Leahy and Tol (2011) rely on the production function approach to estimate the value of lost load for the Republic of Ireland (ROI) and Northern Ireland (NI). For both the considered areas the findings consistently show a VOLL for the industrial sector of about 4 €/kWh, of 13-14 €/kWh for commercials, while higher values characterize the residential (17.95 €/kWh in NI, 24.53 €/kWh in ROI). For ROI, the availability of hourly electricity demand profiles allow a detailed breakdown of the VOLL during the day: for residentials, very low values occur during the night (when the household activity is very limited), they increase at about 30 €/kWh during the day, with some differences depending on the season; finally, they can reach peaks of 60 €/kWh during the weekend. On average, the overall VOLL in ROI is about 12.86 €/kWh. The authors provide also an analysis of the time trend of the VOLL for sectors, and a relevant discussion with important implications in terms of capacity regulation and priority in users shutting off.

Linares and Rey (2013) employ the same methodology for Spain. The authors compute the VOLL measures either in a “standard” way, but also correcting for the possibility of substituting energy dependent activities with other activities during the blackout. The overall VOLL measure ranges from 4.76 €/kWh to 6.88 €/kWh. The average value for non-household (not accounting for limited electricity-dependence) is 5.56 €/kWh, while for household it is 8.79 €/kWh. The authors also provide a comparison of the VOLL measures over time and across Spanish regions. Finally they discuss whether important policy tools such as the incentives to maintain and build generation capacity and the compensation for interruptible services are in line with the estimated VOLL. The comparison show that the former are set at a too low level while the latter are excessive.

Finally, in Praktijnjo et al. (2011) the production function approach is refined for residential users since the authors account for partial substitutability of home activities dependent on electricity with other activities. Moreover, they rely on Monte Carlo simulation to account for uncertainty in the main variables employed in the model. For the agricultural, industrial and service sectors, the authors follow the traditional approach linking value added creation to energy consumption, while for public administration the damage is evaluated in terms of lost taxes. They find an average VOLL for the whole German economy equal to 9.43 €/kWh. The value for residential is 17.40 €/kWh, 6.71 €/kWh for firms, while for public administration 6.12 €/kWh.

### 2.3 Survey-based studies

Survey-methods have been the most commonly used approach to evaluate the cost of outages, either in the academic literature or in study carried on or commissioned by entities belonging to the industry (utilities, regulators).

Balducci et al. (2002) employ survey data on Canadian energy consumers. The employed data were collected by University of Saskatchewan in 1992 and 1996, covering residential, industrial and service users. They constitute the starting point for estimating Sector Customer Damage Functions (SCDFs) for different users categories, where the interruption cost is a function of outage duration. Costs are normalized with respect to annual peak load: this means that the results for different sectors are reported in US \$ / kW.

The findings show that for all sectors, though with different features, the estimated damage is non-linear with respect to duration. Industrial users interruption costs are quite high for relatively short durations (20

minutes), but increase slowly for longer duration (up to 4 hours). On the other hand, commercial and transportation costs grow much more rapidly. The less relevant damage share relates to residential: although the authors acknowledge that “*the lives of American are enormously disrupted during power outages*” (pp.11-12), the monetary costs result, indeed, very limited for this consumer group.

LaCommare and Eto (2006) provide an evaluation based on the econometric estimates of Customer Damage Functions (CDF) of a previous work (Lawton et al. 2003), which in turns relied on data collected by 24 customer surveys conducted by eight electric utilities in the previous 13 years. LaCommare and Eto, then, start from those CDF results and apply a model that accounts also for customers number and type (industrial, commercial or residential), the frequency of the events, and the customer vulnerability (although the lack of reliable information in this sense lead the authors to assume full vulnerability). The model output is the annuals cost of for the whole country (US) due to supply reliability events. The estimated cost for US electricity consumers is about \$ 104 billion annually, where the commercial sector accounts for 72%, the industrial sectors for 26% and residential for 2% only. Momentary interruptions account for the 67% of the total cost, while sustained interruption for 33%. Finally, a sensitivity analysis is conducted to quantify the effect of uncertainty on the main variables employed.

Willis and Garrod (1997) study industrials’ and commercials’ WTA for different power outages scenarios based on a contingent ranking method: the interviewed managers are asked to rank the scenarios from their most to their least preferred. Scenarios are defined in terms of number of additional supply interruptions in one year, their maximum duration and their timing, as well as the amount of advanced notice received. The corresponding compensation is expressed in a percentage of bill reduction. The findings show that the respondents require a 6.6% bill reduction to compensate for one additional outage, and 6.7% reduction for a decrease in the notice period. One minute increase in the maximum duration of outages require a compensation of 0.05%, increasing to 2.85% for an additional hour.

Bertazzi et al. (2005) present the results of a survey-based application commissioned by the Italian Energy Regulator. The survey, conducted in 2003, was based on face-to-face interviews to household and business consumers. They had to evaluate potential interruption scenarios both in terms of direct cost they would have incurred and in terms of WTP to avoid the interruption and WTA to accept a bill discount every time that the outage occurs. The results, normalized on the energy non supplied, are consistent in showing a non-linear path of the damage with respect to the duration, with the highest value per lost kWh for 1-hour interruption (decreasing for longer interruption) and positive and relevant value for very short outages (3 minutes). With respect to 1-hour duration, the direct costs are estimated in 31.18 €/kWh and 145.20 €/kWh, the WTP in 4.61 €/kWh and 13.17 €/kWh, the WTA in 20.96 €/kWh and 98.15 €/kWh for households and business respectively. For regulatory purposes, the authors suggest to consider a range included between the WTP measure as a lower bound and an average of WTP and WTA as an upper bound.

Beenstock et al. (1998) propose a methodology relying on conjoint analysis (based on ranking choice options) able to account for the “status quo bias”, i.e. the tendency of respondents to prefer the current situation, and for the asymmetry between WTP and WTA. Their survey covers residential users only. The results, based on conditional logit estimates, infer values ranging from of 15.56 shekels/kWh (3.31 €/kWh)<sup>2</sup> in spring/autumn in morning/midday to 61.16 shekels/kWh (13.02 €/kWh) in winter afternoon/evening. The authors also compare their findings with contingent valuation results, and find the latter to be much lower

<sup>2</sup> Adjusted for inflation to June 2014 and converted with the exchange rate of June 30<sup>th</sup>, 2014.

either in terms of WTP or WTA. Moreover, the authors remark a more positive attitude on the interviewees side to answer to conjoint analysis questionnaires (based on ranking) than contingent valuation ones, where they were asked to explicitly price each choice option.

A previous work demonstrating the relevance of the “status quo bias” was already proposed by Hartman et al. (1991), with reference to US residential consumers. The authors conducted a preliminary contingent valuation analysis in which respondents were asked to state both their willingness to pay to avoid additional outages and their willingness to accept a compensation for additional outages. In this phase it was already evident that the stated WTA exceeded the WTP by at least three times. The results of the preliminary survey were subsequently used to design a choice experiment, in which respondents were asked to rank different reliability scenarios, linked to different percentage bill variations. In the results the importance of the consumers’ preference for the status quo emerged clearly, with the surprising finding that, even for small service quality improvements, consumers wished to be “compensated”, since the improvement generated a deviation from the status quo. Finally, the level of compensation estimated through the choice experiment largely exceeds the stated WTA level, since, for one-hour outage the latter shows an average value of \$ 13.18, while the former is \$ 95.42.

Targosz and Manson (2007) estimate a total annual cost due to power quality problems to non-households for EU-25. They find a value of more than 178 € billions. Although the number of interviews is scarce (62 over the whole involved territory, covering 16 sectors), this work is interesting since it is an attempt to cover the whole European area. The focus is not on outages only, but on every event of poor power quality (e.g. voltage dips and swells, etc.), while the cost include labour, lost work-in-progress, process slow-down, damage to equipment and other additional costs.

Carlsson and Martinsson (2008) employed a choice experiment to assess the WTP of Swedish households to reduce power outages. Blackout scenarios were described in terms of duration, day of the week and season (winter or non-winter months). The monetary attribute was represented by an hypothetical connection fee to a back-up electricity board. The WTP was estimated by means of a random-parameters logit model, that allowed to compute mean and also individual levels of WTP. The authors found that, as expected, WTP increases with outages duration, and reaches its highest level in winter during weekends. The values ranges from 8.29 SEK (0.93 €) for a 4-hours outage during weekdays to 140.15 SEK (15.7 €) for 24-hours outage in weekend (both in winter).

Reichl et al. (2013a,b) employ, for Austria, a mixed method based on an extended value added function for business and a stated preference approach for households. We decided to mention these contributions in the section of survey-based methods because also for the estimation of the lost value added, public macro-level information has been integrated with survey data.

Indeed, the damage for non-households is based on sector information of value added production and energy demand profiles, but the monetary value is computed on the basis of a sector-specific share expressed as a percentage of daily value-added, which was previously inferred by means of online interviews to firms, and accounts for the electricity dependence of activities. The total damage for non-households includes, in addition to the lost value added, the cost of idle staff, the value of wasted previous efforts and the cost of damage to production facilities.

For households a choice experiment approach was implemented. Respondents were repeatedly asked to choose whether they would prefer to pay a given sum of money or to experience the interruption described in a particular scenario. WTP is then evaluated by means of a censored random coefficient model. The findings

show an average WTP of € 18.35 per household for a 24-hours outage, € 10.5 for a 12-hours outage, € 4.03 for 4 hours and 1.49 for 1 hour.

The results allowed the building of a tool for the macro-economic assessment of the effects of outages with different characteristics in terms of duration and timing. The overall average VOLL ranges from 3.4 €/kWh (in summer evening) to 22.5 €/kWh (in winter morning). The authors also provide examples of the total macro-economic effect of some simulated outages. In Reichl et al. (2013a), an outage of 12 hours involving the whole Austria in summer is found to produce a total loss of about 500 € millions. In Reichl et al. (2013b) a summer 4-hours outage would produce a total loss of about 300 € millions, while a very long outage (48 hours) occurring in winter is expected to generate a total damage of almost 1,800 € millions.

The same methodology has been employed by Garcia et al. (2013) within the SESAME European Project to assess the household willingness to pay to avoid outages. The study carried on the widest survey ever conducted at European level, and the results obtained by means of a random coefficient model could be employed to estimate both the average (0.903 € per hour) and country-specific WTP, with the possibility of accounting for different households and outages characteristics.

#### 2.4 Studies based on market behavior analysis and case-studies

The most representative study based on market behaviour is provided by Caves et al. (1992). The authors employ the information related to (firm) consumers' choice to participate to interruptible and curtailable service contracts, where they receive a compensation if they accept to be completely or partially suspended in the electricity supply under particular conditions. Under the assumption that consumers participate to the contract if the benefit (bill credit) is larger than the unknown expected interruption cost, the latter can be econometrically estimated. The authors employ a probit model<sup>3</sup>, and infer that 1-hour shortage cost is 7.55 – 8.89 \$/kWh. It is worthwhile to point out that the authors themselves highlight the poor significance of the parameters, due to the small quantity of available data. Indeed, collecting a sufficiently wide set of data is difficult, because a limited number of users were eligible to participate to interruptible service contracts (this is true for many electricity markets) and also because information on non-participants are necessary as well. Finally, further assumptions need to be made to identify the interruption probability perceived by users; in this work, the authors have assumed that users rely on past interruption events.

With respect to case-studies, Sierra and Fierro (1997) estimate the outage costs of industrial Chilean consumers by surveying them just after the 1989 electricity restriction, which limited the electricity use by 10% for approximately 45 days. The selected firms were interviewed on the cost they would incur in case of restrictions described by different scenarios. Therefore, the study did not refer to a specific restriction, but the temporal proximity of a real one increased importantly the awareness of respondents when evaluating the suffered damage. The cost includes lost sales and changes in use of production factors, including financial capital related to the variation in inventory and the purchase of equipment needed to face the restriction. The cost estimated for 1-month restriction of 10% is US \$ 0.15. per kWh. This cost could be reduced if selective rather than equi-proportional restriction were applied, i.e. if firms with lower outage costs were restricted before.

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<sup>3</sup> weighted exogenous sampling maximum likelihood probit.

Anderson et al. (2007) employ a particular model (IIM – Inoperability Input-Output Model) able to account for the interdependency in production across different sectors. This interdependency amplifies, by generating cascading effects, the impact of power supply interruptions. The method is applied to the case of August 2003 Northeast Blackout in the US. The results show a total loss of \$ 8.39 billions for three days, of which about one third relates to unfulfilled electric power demand and the remaining part is due to reduced workforce productivity. The results are consistent with previous studies on the same blackout, but with the advantage of providing a sector breakdown of the losses (business services is the most damaged sector). The authors also illustrate the potential application of the method in terms of risk management.

Table 1 – literature review

Contribution	Geographic Area	Methodology	Findings
Caves et al. (1990)	North America	Literature review	Outage costs from previous studies. Residential users: 0.04 - 31.5 \$/kWh. Industry: 2.74 - 48.42 \$/kWh. Commercials: 0.82 - 46.85 \$/kWh.
De Nooij et al. (2007)	Netherlands	Production Function	Whole country: VOLL = 10.89€/kWh 1 hour interruption = 202 € millions (daytime) 128 € millions (evening)  Non-households: VOLL = 7.59 €/kWh  Households: VOLL = 20.84 €/kWh 1 hour interruption = 3.40 € per person (3.03 € during the daytime)
Leahy and Tol (2011)	Ireland	Production function	Republic of Ireland (overall): VOLL = 12.86 €/kWh  Industrial: VOLL = 4 €/kWh  Commercial: VOLL = 13 €/kWh in Northern Ireland VOLL = 14 €/kWh in Republic of Ireland  Residential: VOLL = 17.95 €/kWh in Northern Ireland VOLL = 24.53 €/kWh in Republic of Ireland (above 30 €/kWh midweek daytime, up to 60 €/kWh during the weekend)
Linares and Rey (2013)	Spain	Production function	Whole country: VOLL = 4.76 – 6.88 €/kWh Non-households: VOLL = 5.56 €/kWh Households: VOLL = 8.79 €/kWh
Praktiknjo et al. (2011)	Germany	Production function	Whole country: VOLL = 9.43 €/kWh Residential: VOLL = 17.40 €/kWh Commercials: VOLL = 6.71 €/kWh Public administrations: VOLL = 6.12 €/kWh
Balducci et al. (2002)	Canada	Survey	Industrial: 9.47 \$/kW for 20-minutes interruption 20.97 \$/kW for 1-hour interruption 45.09 \$/kW for 4-hours interruption  Commercial: 7.14 \$/kW for 20-minutes interruption 19.38 \$/kW for 1-hour interruption 66.82 \$/kW for 4-hours interruption  Residential: 0.05 \$/kW for 20-minutes interruption 0.23 \$/kW for 1-hour interruption 2.47 \$/kW for 4-hours interruption  Transportation: 13.42 \$/kW for 20-minutes interruption 24.73 \$/kW for 1-hour interruption 69.20 \$/kW for 4-hours interruption
LaCommare and Eto (2004)	US	Survey	Total cost for the whole country: \$ 104 billions annually  (72% commercial, 26% industrial, 2% residential)

Contribution	Geographic Area	Methodology	Findings
Willis and Garrod (1997)	UK	Survey	Industrial and commercial users WTA = 6.6% of the total electricity bill for an additional outage in one year. WTA= 6.7% for a reduction in the advance notification period WTA = 0.05% for one additional minute of maximum duration WTA = 2.85% for one additional hour of maximum duration
Bertazzi et al. (2005)	Italy	Survey	1-hour interruption Households: direct costs: 31.18 €/kWh WTP: 4.61 €/kWh WTA: 20.96 €/kWh Business: direct cost: 145.20 €/kWh WTP: 13.17 €/kWh WTA: 98.15 €/kWh
Beenstock et al. (1998)	Israel	Survey	Households: Minimum: 15.56 shekels/kWh (3.31 €/kWh) (morning – spring/autumn) Maximum: 61.16 shekels/kWh (13.02 €/kWh) (evening – winter)
Hartman et al. (1991)	US	Survey	Households: Self stated cost: \$ 13.18 for 1-hour outage Choice experiment estimated cost: \$ 95.42 for 1-hour outage
Targosz and Manson (2007)	EU-25	Survey	Annual cost of poor power quality for non-households: 178 € billions
Carlsson and Marinsson (2008)	Sweden	Survey	Households WTP = 8.29 (0.93€) SEK for 4-hour interruption in winter (weekday) WTP = 140.15 SEK (15.7 €) for 24-hour interruption in winter (weekend)
Reichl et al. (2013 a, b)	Austria	Survey	Households: WTP = 1.49 € for 1 hour WTP = 4.03 € for 4 hours WTP = 10.5 € for 12 hours WTP = 18.35 € for 24 hours Average overall VOLL = 3.4 – 22.5 €/kWh 12-hours blackout in summer: total damage = 500 € millions 4- hours blackout in summer: total damage = 300 € millions 48-hours blackout in winter: total damage = 1,800 € millions
SESAME projet	EU-27	Survey	Household: WTP = 0.903 € per hour
Caves et al. (1992)	US	Market behavior	Industrial users: 7.55-8.89 \$/kWh for 1-hour shortage
Sierra and Fierro (1997)	Chile	Case study	Industrial users: 0.15 \$/kWh for 1-month 10% restriction.
Anderson et al. (2007)	US	Case study	Total damage generated by the August 2003 blackout (3 days): \$ 8.39 billions Direct damage for power production: \$ 2.72 billions Damage for lost workforce productivity: \$ 5.66 billions

### 3. EMPIRICAL APPLICATION

#### 3.1 *Choice of methodology.*

After a careful evaluation of the *pros and cons* of the available methods, we have chosen to employ a mixed strategy based on the production function and the stated preferences approaches. Indeed, we believe that these two methodologies can be more easily generalised and then adapted to hypothetical blackout scenarios involving all the users' types.

In fact, the case-study approach has been discarded for the following reasons. The first (and most obvious) reason is that the blackout simulated in the two trials we are considering are purely hypothetical, therefore we do not rely on real blackout information. The second point is the lack of quantitative information on the damages generated by comparable blackouts, i.e. by recent outages occurred in the areas involved in our case studies with similar timing and duration.

The approaches based on market behaviour have as well been considered not suitable, since they require very detailed information on consumers making particular market choice (e.g. users adhering to interruptible service contracts), while the results provided cover a limited portion of the total users population.

Thus, our mixed strategy relies on stated preference (surveys) for households, since we believe that this method better captures the main source of damage for residential users, which is likely to be of psychological rather than of material origin. This choice is also consistent with ESSENCE's aim of measuring the social (in addition to the purely economic) costs of interruptions, although the social aspect is limited to the domestic life of households.

On the other hand, the inconvenience that an interruption generates to the productive sector is mainly of economic source, where the loss of production plays a major role. Moreover the very low response rate registered by the previous studies relying on firms surveys, showed us that implementing a survey-based approach also for the firm segment was not feasible in the context of ESSENCE, leading us to prefer a production function approach based on local macro-level data of production (value added) and electricity consumption, which can be retrieved from public statistics.

Finally, we produce a separate evaluation of the damage incurred by the energy sector operators, referring both to the whole electricity supply chain, and specifically to the generation segment.

#### 3.2 *Non-household consumers: "production function" approach*

As stated above, we have decided to rely on a "production function" approach to evaluate the damage for non-residential users.

This approach presents the important advantage of being of straightforward application, once the necessary macro-economic information is available. In its simplest formulation, relating the total production in a given area to yearly energy consumption, it has been one among the first methods used to estimate the outages cost.

The idea is to evaluate the damage of a blackout starting from a constant measure of Value Of Lost Load (VOLL) computed as a ratio

$$VOLL = \frac{VA}{EC} \quad (1)$$

Where  $VOLL$  is the value of lost load,  $VA$  is the annual value added and  $EC$  is the annual electricity consumption.

The total damage can be subsequently computed by multiplying the  $VOLL$  by the total energy non delivered. The most recent applications, such as those ones mentioned in the previous section, refine the analysis by computing sector-specific  $VOLL$  measures:

$$VOLL_i = \frac{VA_i}{EC_i} \quad (2)$$

Where  $VOLL_i$  is the value of lost load for sector  $i$ ,  $VA_i$  is the annual value added and  $EC_i$  is the annual energy consumption, both referred to the same sector.

In this case the total damage has to be computed by multiplying the specific  $VOLL$  by the energy non delivered to the sector, and subsequently by summing the products. Clearly, this refinement is subject to the availability of sufficiently detailed macro-economic information.

The method based on the production function implies a linear relationship between lost production (expressed in terms of value added) and energy non supplied. It constitutes a proxy of the actual damage that would occur in case of interruption since it relies on several assumption and simplifications (see De Nooij et al., 2007, and Billinton et al., 2001).

- 1) It ignores potential costs related to damaged equipment, which are more likely in some sectors than in others, and which are probably not directly linked to the quantity of energy non delivered.
- 2) It assumes that the damage corresponds to the lost value added, i.e. the value of production net of the external purchases. Indeed, it is in general reasonable to assume that when production is stopped, firms do not employ (i.e. save) material and services (including energy). Nevertheless, in some processes also some external input can be lost. For instance, this is the case of perishable raw materials, or energy in productions where temperature must be kept high or low and an interruption implies re-heating or re-cooling operations.
- 3) It ignores re-starting times, which can be very relevant in some industries and are likely to require large employment of labour for resetting activities.
- 4) It does not consider that some kinds of activities can be carried on even in absence of electricity. Their weight largely depends on the type of production.

The drawbacks described in points 1) to 3) would imply an underestimation of the total damage, while the issue in 4) would lead to an overestimation; these effects are likely to compensate each other. Globally, as pointed out in De Nooij et al. (2007), and Billinton et al. (2001), the model can be considered a valid method to provide a reliable estimate of the order of magnitude of the total damage, for general policy evaluations, which constitute the main aim of this study. Nevertheless, we point out that it could not be sufficiently reliable for accurate sector-specific considerations.

Finally, it is worthwhile to highlight that the potential damage reduction due to the presence of back-up facilities in some firms is not considered. Indeed, the distribution of such equipment across firms is very heterogeneous, also for firms belonging to the same sector, and any assumptions in this sense would constitute, at best, a guess of the actual situation. Moreover, and more importantly, if back-up equipment reduces the impact of interruptions, it is costly in terms of investments. This cost, as mentioned in the previous section, is as well a cost of interruption, since it substitutes the losses in production.

### 3.2.1 Application to the Italian trial

#### 3.2.1.1 Global damage to the productive system

The data available in the Italian public statistics are sufficient to compute sector-specific VOLL measure. Moreover, the available information allowed to estimate, for each sector, the level of energy non-supplied. Therefore, the total damage for the productive system has been computed as a sum of sector-specific blackout costs.

The data on sector value added are published by ISTAT<sup>4</sup>. The national aggregates are available up to the year 2012. However, due to the relevant heterogeneity of Italian production characteristics and mixes, we preferred to rely on territorial data, published up to 2008. Therefore, the value added amounts have been adjusted for inflation to the first quarter of the year 2014 using the production price index for industrial goods.

The data on annual electricity consumption are published by Terna, the Italian TSO, and disaggregated by sector and geographical areas.

Since the sector classifications employed by ISTAT and Terna do not match perfectly, some sectors have been aggregated to ensure perfect correspondence between value added and energy consumption. The VOLL for each sector has been computed using (2).

The very good level of detail in the available information allowed us to introduce a refinement in this analysis: the electricity sector has been excluded from this evaluation, and a separate damage computation will be provided in the following sub-section. Indeed, in our opinion, although a certain level of auto-consumption exists, it cannot be considered completely correct to evaluate the lost production of electricity as function of electricity itself.<sup>5</sup>

The average VOLL computed for the entire local productive system is 5.92 €/kWh. For comparison purposes, we can for instance see that this value is consistent with the findings of Linares and Rey (2013) for Spain (5.56 €/kWh), but it is lower (although of a similar magnitude) with respect to the findings of other studies, for instance De Nooij et al. (2007) for the Netherlands (7.59 €/kWh).

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<sup>4</sup> Aggregates of the territorial accounts for activity branch (see references).

<sup>5</sup> To apply this refinement, data on consumption and value added have been isolated. Terna provides separate consumption information for the electric sector, while value added appears aggregated for electricity, gas and water supply. Therefore we have separated the value for each one of the three branches in proportion to the number of employees in 2008 (obtained by interpolating the ISTAT data of 2001 and 2011), and accounting for the sector differences in the amount of value added per employee (estimated using the data for the local firms included in AIDA, a dataset provided by Bureau van Dijk).

The following table reports the computed levels of VOLL that, multiplied by the amount of energy non-supplied estimated in the trial<sup>6</sup>, generate the blackout damage reported in the last column (total value of 45.7 euro millions).

The partial VOLL measures are in general of the same order of magnitude as in the previous studies, with some exceptions, probably related to the production mix internal to the category. For instance the chemical sector presents a particularly low VOLL, probably due to an orientation to low value chemical production. On the other hand the textile and the construction sectors show higher values.

Table 2 - “Average” damage evaluation

SECTOR	VOLL (€/kWh)	Energy non supplied (MWh)	Lost VA (€/000)
AGRICULTURE	6.73	382.77	2,575.09
INDUSTRY			
Manufacturing of food product, beverages and tobacco	3.02	389.86	1,177.40
Manufacturing of textile and textile products and leather products	10.25	14.38	147.47
Manufacture of coke, refined petroleum products and nuclear fuel, chemical and pharmaceutical	0.35	3,248.13	1,124.18
Mechanical equipment, electric and optical equipment, transport equipment	2.89	544.34	1,573.69
gas	17.90	21.64	387.43
water	1.61	718.89	1,157.41
Construction	59.99	68.35	4,100.49
Industry other	1.96	910.71	1,788.61
TERTIARY			
Commercial	5.35	787.90	4,213.76
Hotels and restaurants	3.33	377.22	1,256.27
Financial intermediation	26.03	53.74	1,398.84
Services (other)	14.89	1,667.00	24,827.31
<b>TOTAL DAMAGE</b>			<b>45,727.95</b>

<sup>6</sup> The total unsupplied energy is computed in the Italian trial on the basis of the local annual consumption and of daily load profile information. The value is then disaggregated by subsector. The total amount of non-delivered energy is 11,734.2 MWh (of which 2,356.6 MWh refer to the residential sector). From this total value we have net out 192.6 MWh of auto-consumption within the electricity sector itself.

As a refinement, we will try to modify our evaluation to account for the fact that some of the considered industries manage activities which are not strictly dependent on electricity supply (as pointed out in Linares and Rey, 2013 – L&R 2013). Construction is an example of such industries. Also for financial services, although strictly dependent on information systems mainly electricity-based, we can assume that the main output (i.e. financial rents on investments) is not lost in case of blackout. Finally, most agricultural activities depend only weakly on supply continuity, with probably an exception for breeding. Therefore we have chosen to provide also a “prudential” version of the total damage, computed by setting to zero the VOLL for construction and financial services, while for agriculture we maintain the 7% of the VOLL, representing the share of breeding on the total agricultural activities in the area. This value can be interpreted as a “minimal” one, since the damage for sectors with evident low electricity dependence has been set to zero, while additional cost components are still not considered. Therefore, this value can be reasonably be taken as very close to the lower bound of the possible damage.

Table 3 reports the results of this prudential computation, highlighting a total damage for non-households sector of about 37.8 euro millions.

Table 3– “Prudential” damage evaluation

SECTOR	VOLL (€/kWh)	Energy non supplied (MWh)	Lost VA (€/000)
AGRICULTURE	0.47	382.77	180.26
INDUSTRY			
Manufacturing of food product, beverages and tobacco	3.02	389.86	1,177.40
Manufacturing of textile and textile products and leather products	10.25	14.38	147.47
Manufacture of coke, refined petroleum products and nuclear fuel, chemical and pharmaceutical	0.35	3,248.13	1124.18
Mechanical equipment, electric and optical equipment, transport equipment	2.89	544.34	1,573.69
gas	17.90	21.64	387.43
water	1.61	718.89	1,157.41
Construction	0.00	68.35	0.00
Industry other	1.96	910.71	1,788.61
TERTIARY			
Commercial	5.35	787.90	4213.76
Hotels and restaurants	3.33	377.22	1,256.27
Financial intermediation	0.00	53.74	0.00
Services (other)	14.89	1,667.00	24,827.31
TOTAL DAMAGE			37,833.78

Finally, we propose a third evaluation applying the electricity dependence shares used in Linares and Rey (2013). The shares should reflect the weight of the processes for which electricity is a necessary input. The authors, however, define the employed shares as a “best guess” of the actual part of value added lost in case of blackout, since no empirical support is available at the moment. However, we can see that this third computation provides a global damage evaluation of a similar order of magnitude with respect to the previous one (34.6 euro millions).

Table 4 – Damage evaluation with energy dependence coefficients

SECTOR	VOLL (€/kWh)	Energy dependence (share)	VOLL CORRECTED (€/kWh)	Energy non supplied (MWh)	Lost VA (€/000)
AGRICULTURE	6.73	0.40	2.69	382.77	1,030.04
INDUSTRY					
Manufacturing of food product, beverages and tobacco	3.02	0.90	2.72	389.86	1,059.66
Manufacturing of textile and textile products and leather products	10.25	0.90	9.23	14.38	132.72
Manufacture of coke, refined petroleum products and nuclear fuel, chemical and pharmaceutical	0.35	0.90	0.31	3,248.13	1,011.76
Mechanical equipment, electric and optical equipment, transport equipment	2.89	0.90	2.60	544.34	1,416.32
gas	17.90	0.90	16.11	21.64	348.69
water	1.61	0.90	1.45	718.89	1,041.67
Construction	59.99	0.40	24.00	68.35	1,640.20
Industry other	1.96	0.90	1.77	910.71	1,609.75
TERTIARY					
Commercial	5.35	0.80	4.28	787.90	3,371.00
Hotels and restaurants	3.33	0.80	2.66	377.22	1,005.01
Financial intermediation	26.03	0.80	20.82	53.74	1,119.07
Services (other)	14.89	0.80	11.91	1,667.00	19,861.84
TOTAL DAMAGE					34,647.74

### 3.2.1.2 Damage to the electricity sector

The cost of blackout for the electricity sector will be evaluated in terms of value of the energy non-supplied to final customers.

For generators, the lost revenues can be expressed in terms of energy not sold evaluated at the hourly market price<sup>7</sup> (the amount of energy non-delivered is net out of the auto-consumption of the electricity sector itself). The following table shows the results, based on the values of the case study.

Table 5 – Damage for producers

Time	Price (€/MWh)	Energy not sold (MWh)	Lost revenues (€)
10	115	2,927	336,655
11	115	2,753	316,696
12	115	2,387	274,548
13	90	1,914	172,297
14	90	1,157	104,138
15	90	403	36,268
TOTAL		11,542	1,240,602

In order to achieve a damage evaluation homogenous to the one proposed in the previous paragraph, expressed in terms of value added, we subtract from the total revenue lost the corresponding cost of gas (the main external input), evaluated in 52.83 € per MWh of electricity produced.<sup>8</sup>

Therefore the total loss in terms of value added can be approximated as follows:

$$\text{VA lost for generators (in current value 2012)} = 1,240,602 - (11,542 * 52.83) = \text{€ } 630,838$$

For homogeneity with the other part of the analysis, we would like to express this value adjusted for inflation to the first quarter 2014<sup>9</sup>.

We get the following

$$\text{VA lost for generator} = \text{636,169.}$$

For the other operators of the electricity chain, it is possible to approximate the total damage using the value of the different components of price (price for residential users in the fourth quarter 2013 is employed), retrieved from CCSE and from the Italian Energy Authority website.

<sup>7</sup> Source: GME

<sup>8</sup> This unitary cost has been obtained by dividing the average wholesale gas price (28 €/MWh) by an efficiency coefficient of 53% (AEEG, 2013).

Therefore, the cost of producing 1 MWh of electricity by means of a thermal plant should generate an average cost of  $28/0.53 = 52.83$  €/MWh.

<sup>9</sup> The consumer price index has been employed.

Table 6 – Damage for the other operators

	Value of the price component (€/MWh)	Energy non-supplied (MWh)	Total damage (€)
Dispatching	10.8	11,542	124,654
Supply	7.7	11,542	88,873
Network	27.7	11,542	319,713
System costs	37.1	11,542	428,208
Taxes	25.4	11,542	293,167
TOTAL			1,254,615

### 3.2.2 Application to the Polish trial

#### 3.2.2.1 Global damage to the productive system

Unfortunately, for the Polish trial, the public information is available with a lower level of detail. In particular, with reference to Warsaw city, data on energy consumption of different sectors are not available. This implies that the sector-specific VOLL measures cannot be estimated at local level. A possible solution could be represented by the choice of relying on national-level data, but a careful evaluation showed that the VOLL levels computed with this approach would relevantly underestimate the damage for Warsaw, due to the concentration of high value-added activities in the capital city.

Moreover, the unavailability of sector specific consumption data would require very strong assumptions in assigning to the different sectors the energy lost during the blackout.

To overcome this issues, we have decided to employ a single average VOLL measure to apply to the total energy non-delivered to non-households<sup>10</sup>.

$$VOLL = \frac{Total\ VA}{Total\ EC} \quad (3)$$

The data on total gross value added are published by the Statistical Office in Warsaw, and the most recent refer to the year 2011. Therefore, the value added amounts have been adjusted for inflation to the first quarter of the year 2014<sup>11</sup>. Data on total consumption are provided by the City of Warsaw, Infrastructure Department. In order to evaluate the VOLL for non-households, we have subtracted the household consumption provided by the Statistical Office in Warsaw.

<sup>10</sup> The total energy non-delivered to non-households is computed reducing the total energy non-delivered due to the outage (5,904 MWh) by the share of households consumption in Warsaw in 2012 (23.43%). The total unsupplied energy is computed in the Polish trial on the basis of the local annual consumption and of daily load profile information.

<sup>11</sup> Consumers price index is employed. This different choice respect to the index applied to the Italian case study is due to the fact that the Polish production price index doesn't include tertiary activities, while these account for 85% of the total added value in the Warsaw area, and we couldn't find any price index for services.

We would like to point out that the available data do not allow to exclude the energy sector from the evaluation. However, we believe that this approximation does not represent a relevant distortion of the results.

The average VOLL computed for the entire productive system of Warsaw is 31.60 PLN/kWh (7.58 €/kWh). For comparison purposes, we can for instance see that this value is consistent with the finding of De Nooij et al. (2007) for the Netherlands (7.59 €/kWh). This could be surprising, if we consider that the price levels of the two countries are very different. However, we again point out that we are focusing on the area of Warsaw, the capital city, which shows a particular concentration of high value-added activities.

We will try, then, to apply the same refinements we have adopted for the Italian case. Therefore, we will try to modify our evaluation to account for the fact that some of the considered industries manage activities which are not strictly dependent on electricity supply (see L&R 2013). This is the case of construction and of financial, insurance and real estate services. We are not considering agricultural activities (which are as well only marginally depending on electricity) since their weight is negligible with respect to the city total value added. Therefore we have chosen to provide also a “prudential” version of the total damage, by reducing the average VOLL by the percentage of value added related to construction and financial services, getting an “adjusted VOLL” of 23.41 PLN/kWh<sup>12</sup>. Also in this case, this value can be interpreted as a “minimal” one, since the damage for sectors with evident low electricity dependence has been set to zero, while additional cost components are still not considered. Therefore, it can reasonably be taken as very close to the lower bound of the possible damage.

Finally, we propose a third evaluation applying the electricity dependence shares used in L&R 2013, which need to be considered with caution for the reasons explained in the previous subsection. The proposed VOLL is therefore weighted by the share of value added produced by each sector and by the electricity dependence coefficient proposed in L&R 2013. This approach lead to an average VOLL of 24.79 PLN/kWh<sup>13</sup>.

Table 7 reports the contribution of different sectors to the total Value Added produced in Warsaw in 2011, as well as the electricity dependence coefficient proposed in L&R, 2013.

Table 7. Shares of value added by sector and electricity dependence coefficients

Sector	Share of value added	Share of electricity dependence (L&R 2013)
Industry	0.084	0.9
Construction	0.059	0.4
Trade and services	0.391	0.8
Financial, insurance and real estate	0.200	0.8
Other services	0.266	0.8

<sup>12</sup> Notice, however, that this approach is not fully comparable with the one used in the previous evaluation related to the Italian case. Now, in fact, the values are not weighted by the sector consumption, which is unknown.

<sup>13</sup> The same considerations illustrated in the previous note apply.

The approach based on “average” value added lead to a total damage results of about 143 millions of PLN (34 million €), while the two “prudential” approaches lead to similar results: 106 millions of PLN (25 million €) and 112 millions of PLN (27 million €) respectively. Table 8 summarizes the results.

Table 8. Blackout damage for non-households.

	VOLL (PLN/kWh)	Energy non- supplied (MWh)	Damage (PLN thousand)	Damage (€ thousand <sup>14</sup> )
"Average" damage evaluation	31.6	4,521	142,852.61	34,257.22
"Prudential" damage evaluation	23.41	4,521	105,828.47	25,378.53
"Prudential" damage evaluation with energy dependence shares	24.79	4,521	112,066.97	26,874.57

### 3.2.2.2 Damage to the electricity sector

Below a specific evaluation is provided for the electricity sector in terms of value of the energy non-supplied to final customers.

For generators, the lost revenues can be expressed in terms of energy not sold evaluated at the market price of the day of the event.

We will employ for this purpose the actual hourly market prices registered for September 21<sup>th</sup>, 2012 (Source: Polish Power Exchange), which will be multiplied by the energy non delivered in each hour of blackout (unfortunately, the available data do not allow to net out the sector auto-consumption).

The following table shows the results.

Table 9 – Damage for producers

Time	Price (PLN/MWh)	Energy lost (MWh)	Lost revenues (PLN)	Lost revenues (€) <sup>15</sup>
10.00	199.54	988	197,061	47,718
11.00	202.14	997	201,619	48,822
12.00	198.85	996	198,109	47,972
13.00	190.35	990	188,494	45,644
14.00	188.50	971	183,048	44,325
15.00	186.19	962	179,040	43,354
	TOTAL	5,904	1,147,372	277,834

<sup>14</sup> Exchange rate of March 31<sup>st</sup>, 2014

<sup>15</sup> Exchange rate of September 21<sup>st</sup>, 2012

In order to achieve a damage evaluation homogenous to the one proposed in the previous paragraph, in terms of value added, we subtract from the total lost revenue the corresponding cost of coal (the main external input), evaluated in 184,541 €. <sup>16</sup>

Therefore the total loss in terms of value added can be approximated as:

VA lost for generators (in current value for 2012) = 277,834 – 184,541 = € 93,293
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For homogeneity with the other parts of the analysis, we would like to express this value adjusted for inflation to the first quarter 2014<sup>17</sup>.

We get the following

<b>VA lost for generators = 95,010</b>
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For the whole electricity chain (in this case, therefore, the remuneration of generators is **included**), it is possible to approximate the total damage using the value of the different component of price (price for medium residential users in the second semester 2013 is employed), retrieved from EUROSTAT.

Since the first stage of the production chain (generation) is included, we provided the damage computation for the entire sector net of the cost of non-employed fuel mentioned above.

Table 10. Damage for the whole sector<sup>18</sup>

	Value of the price component (€/MWh)	Energy non-supplied (MWh)	Total damage (€)
Energy and supply	58.6	5904	345,986
Network costs	53.5	5904	315,875
Tax & levies	31.6	5904	186,573
Total			848,434
Net damage			661,153

<sup>16</sup> This cost has been obtained by approximating the coal wholesale price to 83,97 €/tce (average price in September 2012 for cif- NWEurope. Source: EURACOAL market report 1/2013), and assuming an average efficiency for coal power plants of 33% (World Coal Association).

Since 1 tce corresponds to 8.141 MWh, the computation is the following:

$(5,904 \text{ MWh} / (8.141 \text{ MWh/tce} * 0.33)) * 83.97 \text{ €/tce} = 184,541 \text{ €}$

<sup>17</sup> The consumer price index has been employed.

<sup>18</sup> In current prices for second semester 2013.

### 3.3 Household consumers: survey-based methodology

For household consumers we have decided to rely on a methodology based on surveys, since it is able to encompass all the kinds of damage suffered by a family. Indeed, the inconvenience suffered by this segment of users comes from different sources, involving both material losses (e.g. food spoilage) and non-material damages such as stress, anxiety or impossibility to carry on home activities or to enjoy leisure time. As shown in the literature review, the most updated works pay increasing attention to the latter factors, showing that they account for a relevant part of the global damage occurred to the society.

#### 3.3.1 Willingness to pay vs Willingness to accept

In the literature, the most common approaches rely on willingness to pay (WTP) in order to avoid blackouts. In general, WTP and WTA differ relevantly, with the latter exceeding the former by several times. This is due to several factors, closely interrelated, that Kahneman et al. (1991) classify as “anomalies” in consumers behaviours:

- The *endowment effect*, which is the psychological tendency for an average person to ask a higher compensation to give away something he owns with respect to the amount he would pay to purchase the same good or service.
- The *status quo bias*, which is the tendency to remain in the current state. People in general show a certain resistance to changes, no matter if they involve improvements or deteriorations of the initial situation.
- The former two effects can be seen as a consequence of a more general phenomenon called *loss aversion*, by which any change that generates losses with respect to a neutral reference point is valued more than any change of the same magnitude that generates gains.

Therefore, by choosing an approach based on WTA measures, we expect *a priori* higher results than in studies relying on WTP.

In principle, following the recommendations of Arrow et al. (1993), referring to contingent valuation in the context of cost-benefit analysis at environmental level, WTP measures should be preferred since they constitute a “conservative” choice. Nevertheless, we have chosen a WTA approach for two main reasons. First, we believe that WTA is the correct concept to measure the compensative variation in case of disservice. After a careful evaluation, in fact, we believe it is more respondent to our research target, focused on evaluating a single blackout (which is clearly a disservice situation) rather than more general scenarios describing supply security in terms of interruption frequency and other characteristics, which can be depicted either as service improvements or deteriorations with respect to a given initial state.

Second, also Arrow et al. (1993), point out that the respondents must fully understand and accept the proposed scenario in formulating their responses. We believe that a WTP approach would in this case be not completely suitable, since users’ opinion (this is especially true for residential users) is that continuity is a necessary characteristic of the service they are paying for.

An interruption could represent a sort of “pathological” disservice, for which the electric company would be considered at fault, and it is very likely that many respondents would consider unacceptable to pay additional money to avoid it, or that the WTP expressed would understate the actual value they assign to the interruption.

### 3.3.2 The questionnaire

To implement the chosen methodology based on a residential customers survey, we have decided to rely on a choice experiment, where the choice questions were set in terms of willingness to accept (WTA) blackouts of certain durations, provided that the supplier would have compensated the household with a bill discount. One relevant point, which we paid lot of care to, is that we were asking our interviewees to make choices and trade-offs they rarely face in real life.

In the context of the high service reliability common in most developed country, the experience that the average household has on blackouts is limited, and correctly evaluating and quantifying the consequences is, therefore, difficult. We made an effort to construct the questionnaire in such a way to gradually introduce the problem to the respondent, leading him/her to think about all the possible consequences an outage may have on the household life. Some think-aloud sessions and several pilot interviews were very important to make the questionnaire clear and easier to understand. The questionnaire was composed of several parts. The first one mainly contained the presentation of the problem and some questions aimed to increase the respondent awareness on the consequences of interruptions. Subsequently, we tried to delineate the electricity consumption habits of the household. The “core” part of the questionnaire contained the choice sets, while socio-demographic data were asked in the concluding part.

With reference to the choice experiment part, the respondent was simply asked to state whether or not he would have accepted an interruption of a certain duration, provided that he would have been compensated with a bill discount of a certain amount. Therefore, the choice sets were very simple, being composed of only two alternatives: the “Blackout and discount” alternative, and the alternative with “no interruption and no discount”. In turn, each blackout scenario was defined by two attributes: the duration and the level of discount proposed. Since the aim of our study is to evaluate a single event, we did not characterize the scenarios in terms of “frequency” of interruptions. Moreover, in the introductory part, we contextualize the interruption exactly as it was designed in the trials, i.e. happening in a working day, during the day. Each scenario was designed to start at 10.00 a.m., as the blackouts depicted in the trials.

A total of 28 scenarios (i.e. combination of duration and discount) were constructed, since we have hypothesized:

- 4 duration levels: 1 minute, 2, 4 and 6 hours.
- 7 discount levels: 1, 7, 13, 19, 25, 31, 37 euros.

The choice of the duration levels started from the minimal duration that we believe an average respondent could evaluate, i.e. 1 minute, and we reached (by step of two hours) the maximum duration of the simulated interruptions (6 hours). Also for the discount levels we started from the minimum non-negligible discount (1 €) and, subsequently, we generate 7 levels with constant increase of 6 €.

Clearly, 28 choices would have been an excessive effort for our respondents, with the risk of reducing the quality of the data, or the number of responses.

Therefore, we randomly grouped our scenarios into 7 blocks of 4, and only one (randomly chosen) scenario for each block was presented to each respondent (7 scenarios per respondent in total). The platform employed for the online questionnaire<sup>19</sup> also allowed to change the order in which the different scenarios were presented. Below, an example of a choice task is presented.

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<sup>19</sup> “SurveyMonkey”, <https://it.surveymonkey.com/>

The survey has been mainly carried on by means of online questionnaires, but we needed to integrate with face-to-face interviews and paper based questionnaire to cover customer segments not easily reachable through the internet.

The survey started in March 2014 and lasted about three months. The same questionnaire has been distributed in Italy and in Poland. For Polish respondents, all the monetary values were converted to PLN, with approximation to the closest integer value.

Since we relied on different channels for distributing our questionnaire, including the launch through social networks, we cannot estimate how many contacts we have actually reached, and therefore, we cannot compute a response rate.

We have collected a total of 623 questionnaires (505 in Italy and 118 in Poland), of which 456 contained all the relevant information and could be employed for the estimates.

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**1. The interruption lasts from 10.00 to 10.01 a.m. (1 minute). The proposed bill discount is 13 euros.**

- I am willing to accept this interruption, given the proposed discount.
- I would prefer not having any interruption and any discount.

*Figure 1 - Example of a choice task*

### 3.3.3 Data

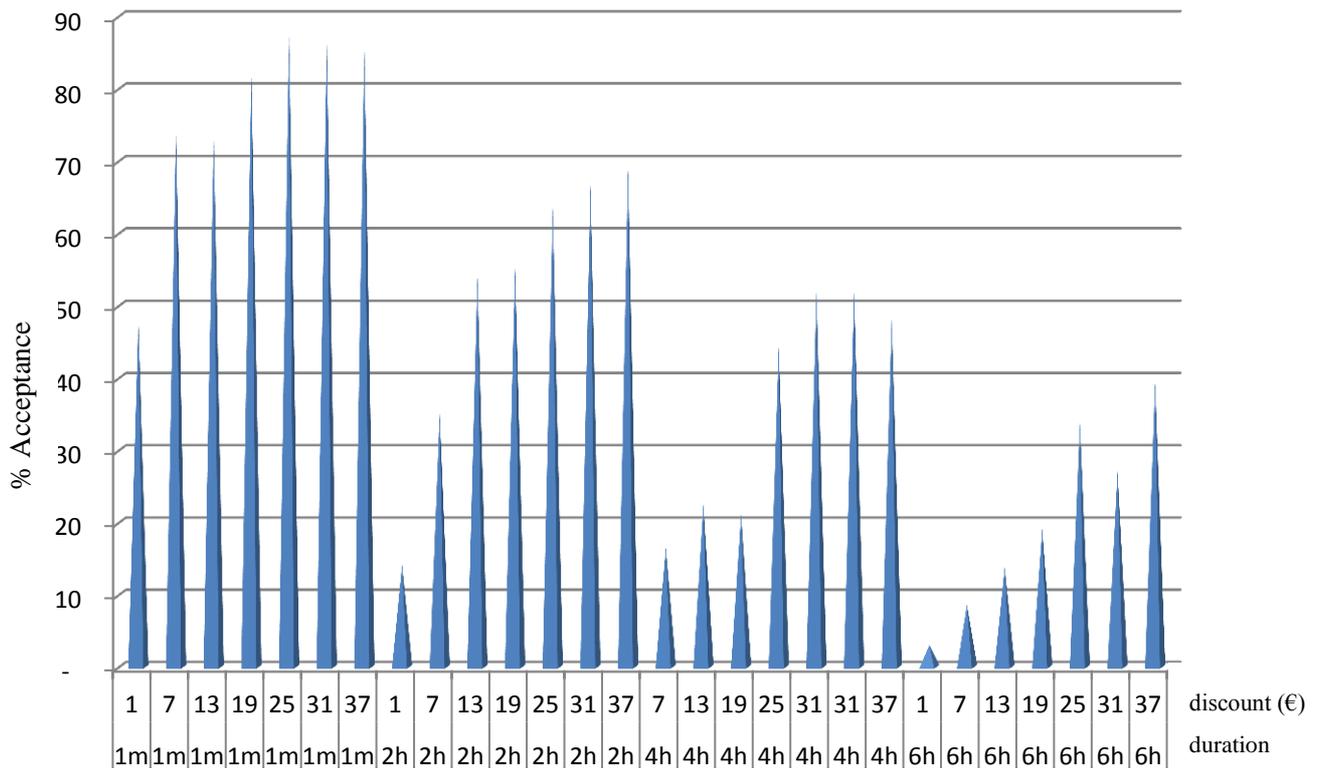
In principle, each respondent generates 7 observations (one for each choice task), but a few respondents did not complete all the choice tasks. Moreover some (124) observations have been eliminated as a consequence of the outliers detection procedure. As a result, our database consists of 3065 observations, of which a 15% share relates to Polish respondents.

A preliminary analysis of the data showed that our respondents behaved, in general, consistently in making their choices. Indeed, as expected, on average the blackout acceptance rate increases for higher discount levels and decreases for longer durations.

Moreover, it is interesting to notice that Polish respondents present a lower acceptance rate (34%) with respect to Italian respondents (46%). This suggests that they are more sensitive to electricity interruptions. Such a difference can depend on cultural reasons.

The following graphs show the path of the acceptance rate for different level of duration and discount, for Italian and Polish respondents.

Italian households



Polish households

Figure 2 – Acceptance rates

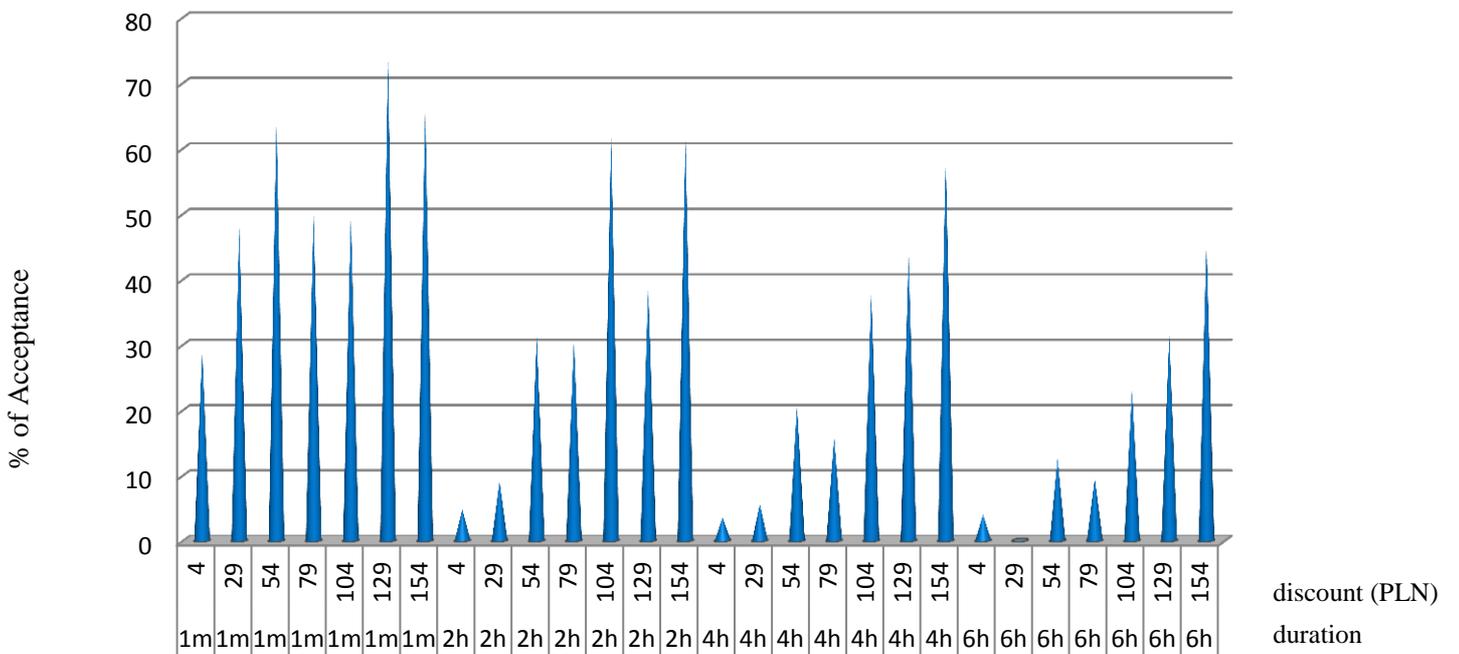


Table 11 – Summary statistics<sup>20</sup>

<u>Variable</u>	<u>Mean</u>	<u>St.dev</u>	<u>Min</u>	<u>Max</u>
choice	0.441	0.497	0	1
dur (h)	2.918	2.244	0.016667	6
disc (€)	18.764	12.014	0.97	37.2
d_pol	0.148	0.347	0	1
d_age18_24	0.1	0.3	0	1
d_age25_44	0.31	0.463	0	1
d_age45_69	0.537	0.499	0	1
d_age70	0.053	0.224	0	1
d_female	0.446	0.497	0	1
d_income_hlevel	0.159	0.365	0	1
d_educated	0.743	0.437	0	1
d_countryside	0.106	0.308	0	1
mec (€)	47.937	26.635	2.415	174.5

Finally, in table 11 we present the summary statistics of the relevant variables:

- *choice* is the dependent binary variable equal to 1 if the respondent has chosen the proposed blackout scenario.
- *dur* is the duration variable in hours.
- *disc* is the discount variable expressed in euros (re-converted in euros for Polish respondents).
- *d\_pol* is a dummy (binary) variable equal to 1 when the respondent is Polish, 0 otherwise.
- *d\_age18\_24*: dummy variable equal to 1 when the respondent is between 18 and 24 years old;
- *d\_age25\_44*: dummy variable equal to 1 when the respondent is between 25 and 44 years old;
- *d\_age45\_69*: dummy variable equal to 1 when the respondent is between 45 and 69 years old;

<sup>20</sup>The summary statistics allow some reasoning on the relationship between our sample and the Italian and Polish population.

With respect to the age classes:

The class 20-24 years represents the 5.2% (Italy) and 7% (Poland) of the total population (in our sample it is substituted by the class 18-24);

The class 25-44 years represents a share of 27.2% (Italy) and 30.5% (Poland);

The class 45-69 years represents a share of 32.9% (Italy) and 32.2% (Poland);

The class 70 years or more represents a share of 16% (Italy) and 9.4% (Poland).

We can see that in our data a remarkable discrepancy emerges for the class 45-69 years, which is over-represented. However, considering that our interviewees are heads of the households, it seems reasonable having an higher share of respondents in this age range. Moreover, we have explicitly chosen to exclude people younger than 18 from the sample. People older than 70 are somehow under-represented due to the difficulties to access online this segment, and to a general reluctance to participate to the survey also in paper version or with face-to-face interviews.

Finally, the share of women on total population is 51.6% in both Countries, slightly under-represented in the sample, but also in this case we believe that it is due to the fact that the heads of household are mainly male.

- *d\_age70*: dummy variable equal to 1 when the respondent is older than 70;
- *d\_female*: dummy variable equal to 1 when the respondent is a woman;
- *d\_income\_hlevel*: dummy variable equal to 1 if the respondent has declared that the economic level of the household is medium-high or high;
- *d\_educated*: dummy variable equal to 1 if the respondent has an high school certification or more;
- *d\_countryside*: dummy variable equal to 1 if the household lives in the countryside, i.e. not in a city, in a town or in a village.
- *mec*: monthly electricity cost. It is the average monthly expenditure of the household for the electricity bill, expressed in euros (re-converted for Polish respondents).

### 3.3.4 Model

In order to evaluate the households inconvenience in case of electricity interruption, let us assume that the variation in utility of family  $i$  if the blackout alternative  $j$  occurs (with respect to the alternative of absence of interruption and discount) is defined as

$$U_{ij} = V_{ij} + \varepsilon_{ij} \quad (4)$$

Where  $\varepsilon_{ij}$  is a stochastic component, while  $V_{ij}$  is a deterministic component that depends on respondent and interruption characteristics and on a set of unknown parameters to be estimated; it is the term we are interested in.

For each choice option, we do not know  $V$ , but we know whether the respondent has chosen ( $y=1$ ) or not ( $y=0$ ) the blackout alternative. The probability of choosing the blackout alternative ( $y=1$ ), with respect to the “no blackout” option, is function of  $V$ , which in turns depends on a set of variables and on the related parameters:

$$PR (y = 1|x) = G(V) = G(x\beta) \quad (5)$$

Where  $x$  is a set of blackout and respondents characteristics.

The functional form  $G$ , finally, is defined through the logit model:

$$G (x\beta) = \exp(x\beta)/(1 + \exp(x\beta)) \quad (6)$$

To conduct the estimates, we have followed the approach described in Bennet e Blamey (2001), that would require to apply the Mc Fadden (1974) conditional logit model. However, when the choice includes only two alternatives, the model can be estimated as a common binary logit model, where the interruption attributes (duration and discount) appear as difference between the two options (see Schultz et al., 2013). Since the alternative “no blackout” has both duration and discount set at zero, the variables are simply the attribute levels. Moreover, since we want to estimate a model without the constant term<sup>21</sup>, we should keep in mind

<sup>21</sup> In such a model, the constant term would capture the average respondent attitude towards the blackout scenario that cannot be explained by the attributes (duration and discount), or, to say it differently, the same attitude when duration and discount

that respondent characteristics can be introduced only if interacted with (i.e. multiplied by) the blackout attributes.

Finally, the empirical functional form of  $x\beta$  that we want to test is the following:

$$\begin{aligned}
 x\beta = & \beta_{DUR} * dur + \beta_{2DUR} * dur^2 + \beta_{DISC} * disc + \sum_{i=1}^n \beta_{ziDUR} * dur * z_i \\
 & + \sum_{i=1}^n \beta_{ziDISC} * disc * z_i + \beta_{PDUR} * dur * d_{pol} + \beta_{P2DUR} * dur^2 * d_{pol} + \beta_{PDISC} * disc * d_{pol} \\
 & + \sum_{i=1}^n \beta_{PziDUR} * dur * z_i * d_{pol} + \sum_{i=1}^n \beta_{PziDISC} * disc * z_i * d_{pol}
 \end{aligned}
 \tag{7}$$

Where

- *dur*, *dis* and *d\_pol* are the defined as in the previous subsection. The *dur* variable also appears squared.

Moreover, the “z” set includes the other variable previously introduced:

- *d\_age18\_24*;
- *d\_age25\_44*;
- *d\_age45\_69*;
- *d\_age70*;
- *d\_female*;
- *d\_income\_hlevel*;
- *d\_educated*;
- *d\_countryside*;
- *mec*: the average monthly expenditure of the household for the electricity bill has been normalized for Italian and Polish respondents on the respective sample median of the variable, to account for the difference in the energy cost in the two countries.

Basically, we assume that the probability of choosing a given blackout scenario (and therefore the associated utility for the respondent) is a function of the blackout characteristics, of the respondent and household characteristics and of the Country of residence.

The base case is tailored on Italian respondents, while the variables interacted with *d\_pol* are aimed to measure whether it exists a significant shift in the parameters when the respondent is Polish.

To say it differently, we want to allow the possibility that the same variables impact differently on the choices of Italian and Polish respondents.

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are set at zero. Since duration=0 implies absence of interruption, and, in any case, we believe that the attributes provide a full descriptions of our (purely hypothetical) scenarios, we have decided to estimate a model without the constant term.

In order to keep only significant variables (since later the parameters will be employed for simulation purposes), a (backward) stepwise procedure has been implemented starting from the full model (model with all the described variable and interactions), and gradually eliminating the non-significant variables, with a critical significance level corresponding to a p-value of 0.1<sup>22</sup>.

Moreover, we employed clustered robust standard errors to account for the potential correlation among observations (i.e. choices) coming from the same respondent.

The estimates of the logit model provide the following results.

Table 12 – logit estimates

Variable	Coefficient	Coefficient value	p-value
<i>Dur</i>	$\beta_{DUR}$	-0.6246	0.000
<i>dur</i> <sup>2</sup>	$\beta_{2DUR}$	0.0432	0.000
<i>Disc</i>	$\beta_{DISC}$	0.0582	0.000
<i>dur*d_countryside</i>	$\beta_{DUR\_COUNTRY}$	-0.2080	0.009
<i>dur*d_age18_24</i>	$\beta_{DUR\_AGE18}$	-0.1669	0.035
<i>dur*mec</i>	$\beta_{DUR\_MEC}$	-0.0525	0.005
<i>dur*d_pol</i>	$\beta_{PDUR}$	-0.1902	0.003
<i>dur*d_age25_44*d_pol</i>	$\beta_{PDUR\_AGE25}$	0.1863	0.015
<i>disc*d_countryside</i>	$\beta_{DISC\_COUNTRY}$	0.0407	0.001
<i>disc*d_age18_24</i>	$\beta_{DISC\_AGE18}$	0.04	0.002

The results show, as expected, that a higher duration reduces the probability of accepting the blackout scenarios<sup>23</sup>. Also the discount term has the expected sign, since higher discounts increase the probability of accepting the proposed scenario.

People living in the countryside are more sensitive to the duration, but appreciate more the discount. In general, and our data support this point, respondents living in the countryside have an higher acceptance rate, meaning the blackout is perceived as less annoying, probably because these individuals are more used to deal with such events, and this fact would lead to a greater appreciation of the offered discount, for a given duration. However, as the duration gets longer, in a rural environment “solutions” to cope with the absence of electricity (e.g. eating out when cooking is impossible, or finding alternative ways to spend leisure time)

<sup>22</sup> The p-value represents the probability of making an error in rejecting the “null hypothesis” that the estimated coefficient is equal to zero (in this case the variable would have no impact on the choice probability). The lower the p-value, the lower the likelihood that the data are consistent with the null hypothesis, and the higher the support to the “alternative hypothesis” of an actual impact of the variable on the choice outcome. A p-value smaller than 0.1 is in general considered as acceptable; a p-value smaller than 0.05 represents a good significance level, while a p-value smaller than 0.01 is considered highly significant.

<sup>23</sup> this effect slows down for long duration levels (as suggested by the positive squared term). Fitted value confirms the decreasing path for all the relevant levels of duration.

are much less readily available. This could be a reason explaining the higher sensitivity to longer interruptions.

The same holds for respondents between 18 and 24 years old, which are as well more sensitive to the duration effect (probably since they are more dependent on electricity-consuming activities), but appreciate more the discount.

Respondents with higher monthly bill are more sensitive to the duration: a reason could be that affording higher electricity costs makes these consumers more exigent with respect to the quality of service.

Finally, Polish respondents' attitude with respect to the proposed discount does not differ significantly from Italians' one: indeed, all the related variables have been dropped in the stepwise procedure since they were not significant.

On the other hand, Polish people are more sensitive to the duration, as shown by the negative and significant interaction. However, Polish respondents between 25 and 44 years old suffer the duration effect significantly less.

The estimated parameters can be employed to predict the utility lost with the interruption in absence of discount ( $V_{nd}$ ), i.e. by setting the discount variable equal to 0.  $V_{nd}$  measures the decrease in utility due to the mere presence of a blackout of a certain duration. To be expressed in monetary value,  $V_{nd}$  must be divided by the marginal utility of the discount variable.

Therefore, the monetary value of lost utility is computed as:

$$\text{Monetary value of lost utility} = V_{nd} / (\beta_{DISC} + \beta_{DISC\_COUNTRY} * d_{countryside} + \beta_{DISC\_AGE18} * d_{age18\_24}) \quad (8)$$

We have simulated three possible values of damage for Italian households (i.e. by setting  $d_{pol}=0$ ):

- the maximum damage, occurring for a family not living in the countryside, with head of the household aged more than 24, with high electricity bill.
- The minimum damage, occurring for a family living in the countryside, with head of the household aged 18-24, paying low electricity bill.
- An average case reflecting a "typical family": not living in the countryside, with a head of household aged more than 24 and an energy monthly cost set at the sample median (€ 39.5).

It is relevant to highlight that we report the damage per family for the minimum (15 minutes) and maximum (6 hours) durations relevant for the Italian trial.

However, we must keep in mind that, as the service is assumed to be gradually restored, different groups of households face different blackout duration, reflecting all the 15-minutes intervals included between the minimum and the maximum.

We get the results described in table 13

Table 13 – Damage for Italian households

Damage	Maximum case	Minimum case	Average case
Damage per household for 15 minutes interruption in €	3.34	1.79	2.86
Damage per household for 6 hours interruption in €	54.57	32.43	43.04
Total damage in € Millions	63.8	36.1	52.5
Average damage per family in €/h	10.88	6.15	8.97
Average damage per person in €/h	4.25	2.41	3.52

On the other hand, to get the results for Polish households we need to set  $d_{pol} = 1$ . Also in this case we simulate three possible levels of damage (here we report only the damage per household for the relevant duration, 6 hours, which is the fixed duration of the blackout simulated in the Polish trial).

- the maximum damage, occurring for a family not living in the countryside, with head of the household non belonging to the age range included between 25 and 44 years<sup>24</sup>, with high electricity bill.
- The minimum damage, occurring for a family living in the countryside, with head of the household aged 25-44, paying low electricity bill.
- An average case reflecting a “typical family”: not living in the countryside, with a head of household aged more than 44 and an energy monthly cost set at the sample median (€ 26.45).

Results are reported in table 14

Table 14 – Damage for Polish households

Damage	Maximum case	Minimum case	Average case
Damage per household for 6 hours interruption in €	73.46	35.31	62.65
Total damage in € Millions	61.05	29.34	52.06
Average damage per family in €/h	12.24	5.89	10.44
Average damage per person in €/h	4.37	2.10	3.73

<sup>24</sup> Simulations on the age range 18-24 cannot be implemented since the age class, poorly represented in the Polish sample, disappeared after the outliers detection procedure.

The higher unitary (i.e. per family) damage computed for the Polish case (for the “maximum” and “average” damage evaluation) reflects the higher sensitivity of Polish interviewees to the blackouts, already highlighted by the estimated parameters and, previously, by the lower acceptance rate of the blackout scenarios.

#### 4. THE COST OF BLACKOUT FOR INDIVIDUAL FIRMS: CASE STUDIES

In the previous sections we have evaluated the blackout costs for firms in terms of lost production. As we have already pointed out, however, other sources of damage can affect the productive sector. The aim of this section is to provide evidence of the importance of emerging costs directly generated by the blackout. Such damages can affect either production lines, or raw materials, or semi-finished/finished products.

Costs deriving from damage are of different nature, and –besides loss of consumption goods – might be costs due to breakage of machinery or internal electric lines, or costs for reactivation of lines up to serious damages making production lines useless beyond any repair. Moreover, such costs can be ascribed either to costs of personnel or costs of materials.

In order to start defining emerging costs which can result in production processes by electric power blackouts, a methodology based on case studies has been adopted. This because determining such costs for a set of industry or a geographic area, or even for a single industry is not feasible in the context of Essence due to the enormous variety of situations.

Thus, the chosen methodology entails the deepening of some cases via interviews, aiming at assessing both the nature of the costs and their values. The economic quantification, in this sense, is particularly complex since it involves to determine costs which are rarely accounted for separately. The three proposed case studies, therefore, differ in the level of depth of information. Nevertheless, we believe they will provide important insights on the variety and the importance of possible additional sources of damage.

The chosen case studies are the following:

- Isolpack SpA (sandwich insulating panels);
- A cement producer;
- A fresh milk producer.

##### 4.1 *Isolpack SpA*

Isolpack SpA is a medium enterprise based in the area of Turin, Piedmont, Northwest Italy.

Its NACE/ATECO 2007 code is 251100 - Fabbricazione di strutture metalliche e parti assemblate di strutture (building of metallic structures and assembled parts of structures).

Its turnover (revenues from sales and services) for 2012 has been of € 55,968,803. It employs currently 67 employees.

Its core business is the production of sandwich insulating panels. Such panels are produced creating two ad-hoc shaped metallic foils, and subsequently injecting a polyurethane foam between the two foils. The foam ensures both thermal and acoustic insulation. Alternatively the filling can be made of rock wool.

The production process is performed in continuum. In the plant several production lines are present. Three lines produce polyurethane-filled panels, two lines rock wool filled ones. All the lines might theoretically work in a 24/7 continuum cycle. In practice production suffers seasonality and thus production flow depend quite heavily on the period of the year. This also because the time-to-market is very short. In

order to reduce storage costs, production is almost “just-in-time”; in some cases produced panels are directly loaded onto trucks and sent to the building site where they are installed. This fact underlines that a stop in production due to black-outs may in some periods generate huge problems in terms of customer satisfaction or reputation.

In order to assess emerging damages due to blackouts several components must be taken in consideration.

The first component depends on the production technology, and applies only to polyurethane-filled panels production. This is the cost of cleaning and reactivating of lines. It is due to the fact that polyurethane, once sprayed on the metallic foil that should enclose it, continues expanding with time. Thus, if it is not contained between the two metallic foils, continues growing, and eventually fills the working space of the production line. Thus, after the end of the blackout, a certain amount of time and effort of workforce is needed to clean the workspace of the line. This does not happen for the production lines working with rock wool filling.

The second component applies to the whole production plant, and is due to the search-and-retrieval and subsequent repair of damages due to the blackout itself.

The third and last component again applies to polyurethane-filled panels production. This component is the cost of waste, and is due to the meters of panel that are damaged by the expansion of polyurethane and have to be thrown away. The number of meters depends in turn on the speed of production (meters per minute) of continuum lines. This is dependent on the type of product.

Finally, it must be noted that the firm has provided to acquire a park of batteries able to supply to short blackouts (lasting up to tenths of second) for all the production plant, at a total cost of about € 80,000.

About the nature of the costs that are described below, it must be pointed out – before describing the cost equation – the nature of the single cost entries in terms of their characteristics of fixed/semifixed/variable costs. The three components are variable, as their value basically depends on the number of production lines at work at the moment of the blackout,  $N_L$ . Nevertheless at the end of the case study an average value of  $N_L$ . (mediated over yearly productivity) has been estimated.

From the above reported description the following cost equation can be defined:

Black-out cost function ( $B_{CF}$ ):

$$B_C = R_C + D_C + W_C$$

That is, reactivation costs, damage costs, waste costs, where in turn:

$$R_C = 5 \times (2H_C) \times N_L$$

5 = number of persons working on a single line;

2 = number of hours needed to clean up the line;

$H_C$  = personnel hourly cost  $\approx 18$  €;

$N_L$  = number of involved production lines = 1 to 3 (mainly depending on timing and season of black-out);

$$D_C = K_1 \times [(K_2 \times H_C) + B_C + (K_3 \times 5 \times H_C \times N_L)]$$

$K_1$  = constant, probability of a damage caused by Black-out ( $\approx 75$  %);

$K_2$  = constant, number of man/hour needed for searching and repairing the damage;

$K_3$  = constant, number of hours of inactivity of the personnel (5) working on the line due to search and repairing of damages;

$H_C$  = personnel hourly cost  $\approx 18$  €;

$B_C$  = cost of repairing;

$N_L$  = number of involved production lines = 1 to 3 (mainly depending on timing and season of black-out);

$$W_C = n \times M_C \times N_L$$

$n$  = waste meters of linear production (usually 8 – 10 m);

$M_C$  = cost of a meter of product;

$N_L$  = number of involved production lines;

$K_1$ ,  $K_2$ ,  $K_3$ ,  $B_C$  and  $M_C$  have been estimated out of the effective costs of the last occurred blackouts.

For what about the assessment of  $K_1$  the four 2013 blackouts resulted in three damages to the electric equipment of the firm. So  $K_1$  should be estimated as  $\approx 75$  %.

Again according to 2013 data,  $K_2$  should be estimated in about 4 hours and 2 persons, total 8 man/hours, and  $B_C$  as about € 1200 (the cost of 4 electronic boards, costing € 290-330 each). Accordingly  $K_3$  is four hours.

Finally, about  $W_C$ , for each blackout 8-10 meters of panel should be discarded for each line, at an average (over the total production) price at sale of 15 €/meter.

Assessing  $N_L$  is more tricky, as this value (between 1 and 3) depends on the period of the year (late spring - beginning of summer is the period when production peaks). It can be considered in the following assessment of production loss, which completes the above emerging cost equation.

An estimate of the maximum possible production gives us the value of 6,082,000 meters of panels per year. This is obtained as follows:

Average production = 8 m/min (average production) = 480 m/h = 3480 m/shift (8 hours) = 11,520 m/day.

Daily production = 3 (lines) \* Average production = 34,560 m/day.

Daily production \* 220 (working days in a year) \* 0.8 (efficiency)  $\approx 6,082,000$  m/year =  $Y_p$ .

The real production is lower, and is about 4,250,000 meters/year =  $R_p$ . As the total number of hours per year is equal to 24 hours x 220 working days/year x 3 lines = 15,840 hours, the average (on yearly basis) production per hour per line is about 268 meters. Thus, given the above average (over the total production) price at sale of 15 €/meter the average loss of production for an hour of blackout is roughly € 4,024 per hour blackout.

Given the above values, we can estimate  $N_L = R_p/Y_p * 3 = 0.699 * 3 = 2.096$

Thus we calculate  $B_{CF} = R_C + D_C + W_C$ : € 377 + € 1573 + € 251  $\approx$  € 2,200

This value is averaged over the yearly productivity. If we want to deal with the maximum costs of specific blackouts, then the number of production lines  $N_L$  must be considered in three separate cases. Then, summing up,  $B_{CF}$  is equal to:

$$B_{CF} = (5 * 2 * 18 * N_L) + ((8 * 18) + 1200 + (4 * 5 * 18 * N_L)) + (10 * 15 * N_L) = \\ = 180 * N_L + (1344 + 360 * N_L) + 150 * N_L;$$

Table 1 contains the costs for each component and each of the three cases, as well as the totals. In the above reported equation and in the table the value of  $K_1$  is obviously 1, as in this case we are not dealing with the average blackout but with the maximum costs of specific blackouts. The last line in the table

contains the full value of lost production for the three cases. This is calculated simply multiplying the average value of linear meter of product (€ 15) times the full productivity of each line (480 m/hours) not taking in account any correction (efficiency, average yearly production, etc.).

Table 15 – costs in € for each case

	$N_L = 1$	$N_L = 2$	$N_L = 3$
$R_C$	180	360	540
$D_C$	1,704	2,064	2,424
$W_C$	150	300	450
TOTAL	2,034	2,724	3,414
Loss of production	7,200	14,400	21,600

It is easily seen that, although  $B_{FC}$  should not be considered as irrelevant, the costs deriving from loss of production become quickly (after about half an hour's blackout) predominant. In fact the blackout cost  $B_{CF}$  is not time dependent, as the damage is produced within minutes (or even seconds in case of the component  $D_C$ ) from the blackout. The presence of the battery backup system actually allows the continuity of production for shorter blackouts, which can more easily occur. Nevertheless in case of serious and prolonged blackouts the backup system is obviously not effective.

#### 4.2 Cement producer

The focus of this case study is a company operating in the production of cement, concrete and construction aggregates. Although the group is large and operates worldwide, our case involves the operations of a relatively small branch.

This plant operates mainly in grinding activities, employing 50 workers, 10 of which are devoted to R&D activities. The plant has a productive capacity of 700.000 Tons per year. At present it is operated at a saturation level of about 60% of its capacity, also due to the general economic crisis, which had relevant impact on the civil engineering and building industry.

The production process is continuous and the activity is organized in three work shifts, while the distribution-related activities are not continuous and involve two work shifts.

The plants receives the clinker (the main raw material) daily and transforms it into cement employing grinding processes involving one or more mills, with the addition of other components. The factory produces 5-6 different types of cement.

The product is then stored in silos and later distributed to the customers, either unpackaged or bagged.

The plant owns also a small cement kiln, employed for the production of a particular type of clinker. It has a capacity of about 150 tons per day<sup>25</sup>.

<sup>25</sup> To give a rough idea of the plant dimension, we must consider that a "large" kiln can produce 5000 tons per day

The whole process is highly electricity dependent: this source of energy is necessary for most activities, including material transfer, mills and machinery operation and rotation of the tubes of the cement kiln. Moreover, all the electronic supports to the production need a continuous and stable supply of electricity.

Nevertheless, the factory has subscribed an interruptible service contract (2MW, covering the average power employed by the whole plant), which has been considered highly convenient from an economic perspective, although it requires relevant investments for the firm (for instance in term of UPS, generators and reset procedures). This fact allows a more easy evaluation of the consequences of an interruption, bearing in mind some relevant points.

First, it is important to notice that the effects of an interruption in electricity supply differ relevantly depending on the time of the day the blackout occurs at. Indeed, the most energy-consuming activities are carried on mainly during the night, in order to enjoy more favourable electricity tariffs, while other activities (e.g. related to product packaging and distribution) are more concentrated during the day. Second, statistically, the interruption related to the interruptible service contract are in general very short (few minutes), but the re-starting time is relevant. An interruption of 3-4 minutes implies about 1 hour to re-start operations, since all the reset activities have to be carried out manually.

In general, the first effect of an interruption is a stop in production; quite obviously, the longer the interruption, the larger the amount of lost production. Globally, we can say that an interruption generates losses in production proportional to the interruption duration, plus a fixed re-starting time of one hour.

This fact is not likely to generate problems in terms of customer satisfaction or reputation (except for long durations in periods of high demand or in case of particular orders), since the process is mainly oriented to produce warehouse. However, from the mechanical point of view, some problems can occur to the equipment (e.g. mills) in terms of blockage or obstruction, since the physiological operation procedure do not foresee production breaks when the machinery is full. This fact would require maintenance interventions.

Damages to the electric equipment are also likely, although the direct link with interruption is not evident or easily demonstrable.

Electronic equipment is very sensitive to interruptions, and protected by UPS in order to avoid damages and data losses. This back-up facilities are effective for short-medium blackout durations. If the duration is relevant (5-6 hours) the UPS support could not be sufficient.

The most delicate process relates to the firing activity. The kiln operates at very high temperatures (1300°-1400°), and natural gas constitutes the main fuel. In case of interruption in the electricity supply, a generator<sup>26</sup> allows to maintain a slow activity of the kiln: a sudden block, at such a high temperature, could bend the tube of the kiln itself. For the same reason, the temperature must be reduced. Therefore, once the service is restored, the kiln must be heated again, and the operation requires time and a relevant amount of natural gas. Also in this case, the longer the interruption, the broader the temperature fall, and so the higher the cost of re-heating, which can be roughly estimated in the range of 500 – 1000 €. Finally, the material present in the kiln can undergo only small temperature falls (about 20°). Larger variations make the product not suitable for sale. It can only be recycled in small proportions (5-10%) as input. An interruption, therefore, generates about 7-8 tons of product to be recycled<sup>27</sup>.

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<sup>26</sup> The generator for the kiln and the UPS are the only back-up facility present in the factory.

<sup>27</sup> We should bear in mind that this damage estimates refer to a very small kiln and are not generalizable to average plant operating in the same sector.

### 4.3 Milk producer

The object of this case study is a dairy firm located in the North of Italy, employing about 50 workers. The prevailing capital share belong to small-sized milk producers located in the surrounding area, which also provide most of the raw material treated. The firms supplies customers and distributors located in Northern and Central Italy.

The operations involve two main activity branches: the first one relates to the treatment, packaging and delivery of fresh milk and cream, while the second one is mainly related to storage and distribution of other dairy products, not internally manufactured.

The production process of the fresh milk starts with the daily milk collection from the local producers by means of tankers, followed by a preliminary laboratory test of the adequacy of its characteristics. Then the milk, already cooled in the previous phases, is further cooled down to 4° C. The treatment phases, including pasteurization, follow this preliminary stage. Pasteurization is a very important process aimed at sanitizing the product and increasing its commercial life and requires a temperature of 76° C.

After the treatments, the milk, cooled again at a temperature of 2-3°, is stored in caulked tanks, and then sent to the packaging process, stored in refrigerating rooms and finally distributed through refrigerated vehicles.

At the end of the process all the plants have to be washed and sanitized.

The fresh cream production follows a similar process, although on a smaller scale and with a slightly different thermal program.

This production process is strongly dependent on electricity and continuity of supply plays a crucial role. In fact, it is relevant to remark that, when dealing with fresh milk, the production cannot be shifted from one day to another. Even if the production process starts at 4 AM and stops at about 2 PM, a delay of few hours creates relevant problems in the product distribution for the following day.

In particular, electricity is employed for the following purposes:

- Operation of all machinery in production lines;
- Production of steam for the heat exchangers employed in pasteurization;
- Production of icy water employed in pasteurization and in the cooling processes;
- Cooling of the refrigerating rooms.

In such operational context, an electricity interruption can generate relevant inconvenience, especially if it occurs in the “peak” production hours, namely between 6 AM and 1 PM, when most of the processes are operating. Although some machinery is equipped with accumulators, these are largely not sufficient to ensure the operation of the whole plant. Moreover, the firm does not possess its own generators.

In a specific case of necessity occurred in 2003 (due to a voltage transformer blown out), the firm could retrieve a back-up facility thanks to the electricity maintenance firm. In this case, the power provided was sufficient to face the emergency, letting the core processes restart in about 8 hours, but not to ensure the ordinary management of the production.

Pasteurization is by far the most sensitive process: even a very short power interruption (few minutes) can generate a fall/rise in the operational temperatures (by stopping the pumps circulating hot and icy water), which makes necessary to stop the production. In fact, very small deviations from the physiological pasteurization temperature (76° C) are possible: Italian regulations do not allow cooling the milk below 72.5° C in the process. Nevertheless, quality rules adopted by the firm set the limit at 74° C. When the

temperature of pasteurization is lower than this, the process stops and the milk contained in the pasteurizer is lost (the capacity is 600 litres). In fact, milk cannot undergo more than one thermal treatment. Case-by-case evaluations are necessary to decide whether the material must be disposed of or it can be allocated to an alternative use (e.g. cheese production). If we consider an average price for raw milk of about 45 €/100 lt., we can estimate a direct damage of 270 € (approximately 2% of the daily value added)<sup>28</sup>. This cost can be considered as fixed with respect to the blackout duration, since, as mentioned above, it occurs even in case of very short interruptions. Moreover, production cannot be re-started immediately, since washing and sanitization activities of the machinery are needed.

Another point relates to the potential damages to electronic equipment, which, although protected, are in some cases very sensitive to sudden variations of electric tension.

Brief interruptions do not generate other relevant problems. Longer blackouts, instead, can have important consequences if they impact on the preservation of the cold chain. In general, however, interruptions of the length considered in this study (i.e. up to 6 hours), are not likely to damage the product stored in tanks or in the refrigerating rooms, since the caulking ensures sufficient autonomy.

The main problems related to interruptions of several hours (if they occur in the “peak” production time) refer to the stop in the production cycle. Clearly, the problem is more relevant if the blackout is unplanned. Since fresh milk is a daily product, lost production cannot be recovered in the following days. Moreover, the inconvenience could also affect the upstream branch of the supply chain, since the storage capacity of the producers is limited, and the milk has to be collected every day.

Finally market issues have to be considered. Fresh milk is a highly competitive sector, and punctuality plays a crucial role in the relationship with customers, generating an organization much similar to a Just-In-Time approach. Not respecting the supply deadline can compromise the contract and potentially lead to a loss of customers. Although this effect is not a “social” damage as defined in this study (the customer lost for a producer is a new customer for another producer), the economic impact for the firm is huge (constituting probably the main source of damage), though difficult to be quantified.

## 5. CONCLUSIONS

This report provides an economic quantification of the benefits of implementing security standards, expressed in terms of avoided costs of blackouts.

We employ a mixed methodology relying on the “production function” approach for the non-household sector, while an econometric method based on survey data (stated preferences) is used for household consumers. Finally, a separate evaluation is carried on with reference to the electricity sector.

The evaluation is applied specifically to the hypothetical blackouts described in the Italian and Polish trials, and follows precisely the blackout scenario, including time and geographical framework, type of customers, features of the economic system, recovery process.

With reference to the Italian case, we find a total damage for non-households ranging from 35 to 46 € millions, while for the residential segment the blackout cost is between 36 and 64 € millions, with a believable value set around 52 € millions considering the characteristics of the average consumer in that area. The damage for the electricity sector due to the energy non-sold is about 2 € millions.

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<sup>28</sup> Our estimate.

In relation to the Polish trial, we find a damage for non-households of 25-35 € millions, while for households the range is between 30 and 61 € millions. If we consider the characteristics of the average residential consumer, we get a total cost of about 52 € millions. For the electric operators the damage is about 0.7 € millions. It can be observed that the estimated damage for household is in both cases higher than the one concerning the economic sector. The damage for the electricity sector (not taking into account the damage to reputation) is just a very small fraction of the total estimated damage.

Finally, since for non-households, only losses in production are considered, we provide, in a separate section, three case studies highlighting different types of additional costs that can occur to firms. Although they are very different in terms of source and of economic impact and are very difficult to quantify, it emerges that their magnitude can be relevant.

The features of this impact vary a lot, even within single industries and do not depend only on the type of production process, but also on the organisation of the firm and of the whole value chain. In general we observed the presence of fixed costs which appear even in case of very short blackouts; other costs are, on the other hand, time dependent but the trend is generally discontinuous, with additional components of cost appearing after some time threshold, typical of every firm, is crossed. Types of costs include: spoiled raw materials or products (or their depreciation), staff-cost for extraordinary maintenance and damage repair, restarting times, damages to production or electrical equipment, extra organisational costs for just-in-time processes. Firms which base their competitive advantage on reduced time to market would also suffer in case of blackouts, of losses in reputation and in customer satisfaction which are difficult to quantify, but which could prove relevant in highly competitive markets.

Moreover, other kinds of damage are not included in the quantitative evaluation, namely the social costs related to the availability of essential collective services such as public health, public security, transports, or communications.

For these reasons, what we provide here must be considered as a “lower bound” evaluation of the potential overall damage occurring in case of interruptions with the features described in the Italian and Polish trials.

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