Chapter 3
The ESSENCE project: a re-examination guided by emerging academic contributions

CLEMENTINA BRUNO, FABRIZIO ERBETTA

Università del Piemonte Orientale, Dipartimento di Studi per l'Economia e l'Impresa, Via Perrone, 18, 28100 Novara, Italia.

Corresponding author(s): clementina.bruno@uniupo.it

ABSTRACT
Improving power network security against cyber-attacks is paramount. The ESSENCE project evaluated the costs and benefits of implementing security standards, focusing in particular on the benefits of enhanced security, specifically in the form of avoidance of blackouts, intended as a non-market good. Drawing on a comprehensive literature review, we defined a mixed-method approach adopted for two distinct case studies: Italy (generation phase) and Poland (transmission network). For household users, we emphasize the rationale behind a stated preference method utilizing a Willingness-to-Accept (WTA) choice experiment. Conversely, for non-household users (industrial sectors), the utility of a production function approach is highlighted for calculating the Value of Lost Load (VOLL) based on macroeconomic data. Re-examining the ESSENCE project in light of recent literature underscores the vital importance of evaluating diverse and comprehensive outage costs in the assessment of power network security.

KEYWORDS: Blackout damage, production function approach, willingness-to-accept, ESSENCE project.

DOI: 10.23760/2499-6661.2025.24_03
ISBN: 978-88-98193-39-4
ISSN (online): 2499-6661

HOW TO CITE
Bruno, C., & Erbetta, F. (2025). The ESSENCE project: a re-examination guided by emerging academic contributions. In Ragazzi, E., Finardi, U., & Vallette d'Osia, J.C.M. (eds.). *Cybersecurity and data protection. in the electricity sector. State-of-the-art of the literature and evaluation methods* (pp. 45-52). Quaderni IRCrES 24. CNR-IRCrES. http://dx.doi.org/10.23760/2499-6661.2025.24_03

1 ESSENCE OBJECTIVES AND THE VALUE OF SUPPLY SECURITY

The ESSENCE (Emerging Security Standards to the EU power Network controls and other Critical Equipment) project was aimed at evaluating the costs and benefits of the implementation of particular security standards to the electric system. The evaluation was based on two case studies describing hypothetical system failures that, under very particular conditions, can arise as consequences of malicious cyber-attacks. One case study involved the generation phase and focused on Italy, while the other one involved the transmission network and was focused on Poland. (Ragazzi and Stefanini, 2019; Abrate et al., 2016; Bruno et al., 2015; CERIS – CNR RT. 47, 48, 51, 52, 53, 55, 56, 57).

In particular, our team was involved in the benefit evaluation, i.e. facing the complex task of evaluating improved security. As previously discussed in this work, there are some situations, such as the one considered in ESSENCE, in which security shows some features common to other public goods, since it is non-rival, non-excludible and not traded on the market, therefore it cannot be valued on the basis of market prices

Therefore, it required an approach for evaluating non-market goods, which could be suitable for being applied to the electricity sector. A deep analysis of the literature led us in the field of evaluation of the damage deriving from blackouts (the negative consequence of security failure considered in the two case studies), an issue that at that time had been addressed by relying on a variety of methods.

1.1 Which methods in literature fitted our case studies?

A crucial starting point for the choice of a methodology has been represented by the taxonomy proposed by De Nooij et al. (2007). The authors consider approaches deriving from different scientific backgrounds, not necessarily rooted in statistics or econometrics. We considered the advantages and disadvantages of all the discussed methodological categories.

- The revealed preference methods are based on the observation of real users' behavior with respect to power outages. Examples of observable behaviors include investments in back-up facilities or the acceptance to adhere to interruptible contracts, representing choices allowing the researcher to infer information about the value assigned to supply continuity. Unfortunately, such behaviors are observable for very limited consumers' segments.
- The case studies usually consist of listing and quantifying damages or developing a survey immediately after a real blackout. The reference to an actual (not hypothetical) fact improves the reliability of the results, which, however, are difficult to use for evaluating other events of the same nature.
- Stated preference methods rely on micro-data collected through surveys and aim at asking for or eliciting the value of supply continuity (or of failures with the features desired by the researcher) in terms of Willingness-to-Pay or Willingness-to-Accept (WTP or WTA). The main advantage is related to preference information directly collected from the respondents, but we must be aware that responses can be affected by different types of biases of cognitive origin. Particular attention should be given to the framing of the questions.
- Another option is represented by the production function approach. The basic idea relies on the assumption that no productive activity is possible in absence of electricity, therefore the total damage is proportional to the amount of energy non-supplied during the blackout, assuming a constant ratio between GDP or Value-Added measures and the corresponding amount of energy consumed in a given area in a time unit. This approach can be refined by considering non-complete dependence of some activities on electricity, different Value-Added / Electricity ratios in different sectors or input-output matrices for considering interdependencies among sectors. Some authors adapt the approach to individual

consumers or families, by measuring the damage in terms of lost leisure time, for which a value must be determined (usually starting from the salary level in the area). This approach is often classified as a "proxy method", since the computed damage represents, in any case, an approximation, since "non-linearities" are difficult to be included (e.g. long restarting time or damages to equipment).

For examples of applications of the different methods in the literature, see RT n. 52, 55, 56 (2014) CERIS-CNR and Abrate et al. (2016).
In the literature, we can find examples of mixed approaches, such as that provided by Reichl et al. (2013a, b), who rely on a production function approach for the productive sectors (improved by firm surveys) and on a stated preference methodology for households.
A mixed approach, as we will illustrate later on, has been judged to be the best option also for ESSENCE. The reasons leading to this choice relate to the nature of the project, that required to evaluate hypothetical blackouts, and to cover the largest possible set of user categories. The production function approach was judged as sufficient to account for the damage suffered by the productive sector, which is mainly of economic and productive nature, with the advantage of relying on secondary (macroeconomic) data, thus avoiding the issue of direct data collection from firms, a segment likely to show relatively low response rates to surveys. The stated preference method, instead, has been found to be suitable for household users, since in this case a relevant source of damage (probably, the main one) is not monetary, but is of social or psychological nature.

Table 1. Advantages and disadvantages of the considered methods

Methodology	Advantages	Disadvantages
Revealed preferences	Based on observable market behavior.	The relevant market choices involve very narrow consumers' segments.
Case study	Damage quantified after observing a real event.	It is very difficult to rely on the results for evaluating other blackouts.
Stated preferences	Damage value directly inferred from the preferences declared by consumers. Can be adapted to hypothetical events.	Potential bias of cognitive origin. The framing of the questions is relevant.
Production function	Relatively easy to apply (also for hypothetical events), once secondary macro-level data are available.	The estimated damage represents a proxy of the total one.

Source: our elaboration from De Nooij et al. (2007) and RT. 52, 55, 56 (2014) Ceris-CNR.

1.2 Outage costs: ideas from a subsequent study.

An interesting contribution by Ericson and Lisell (2020) identifies some dimensions that determine outage costs (p. 97).

- Magnitude, in terms of lost load (which is considered by the largest part of the contributions on this theme).
- Perspective, identifying the subject (individual or entity) that is involved in the blackout;
- Timing of the outage.

- Duration of the outage.
- Advanced warning (or not).

Interestingly, the authors develop an approach aimed at including all the possible damage sources, and identify three cost components:

- Fixed costs, not depending on the outage duration (e.g. data losses or damages to equipment).
- Flow costs, depending on the lack of energy, which can increase, decrease or remain stable over time depending on the ability of users to cope with the outage (e.g. by moving workers to non-energy-dependent activities).
- Stock costs, depending on spoilage of materials, expiration of obligations or even vandalism.

The authors include in the cost categories also damages to households or particular sectors such as health care.

2 CONCEPTUAL FOUNDATIONS OF THE METHOD FOR THE ASSESSMENT OF THE COST OF THE BLACKOUT FOR HOUSEHOLD USERS

As regards household users, the assessment has been thought about as based on the impact on the daily living activities. In this respect a stated preference method has been identified as the most suitable. In this context, two approaches could be used: the measurement of the willingness to pay (WTP) to avoid a blackout and the measurement of the willingness to accept (WTA) a blackout. The two approaches are based on a different conceptual framework. The first implies the willingness of users to pay an amount of money to avoid the adverse situation, while the second implies the willingness to accept that the adverse event occurs in exchange for a compensation (in ESSENCE, a discount on the bill). While the first approach seems conceptually based on the behavioural assumption of non-industrial users that the departure from a status quo is always undesirable, the second is based on the more contingent logic that users pay to have the guarantee of a service and may not be a priori willing to pay an extra-amount to avoid a non-tolerated disservice. Rather, they may be more inclined to think in terms of discount when faced with the acceptance of a negative event.

Actually, such a decision is not trivial, since the literature demonstrates that the two approaches usually lead to different value quantifications, with WTA providing larger (in some cases, much larger) values than WTP, due to some anomalies characterizing consumers choices, such as the endowment effect, the status quo bias and, in general, the loss aversion issue (Kahneman et al., 1991).

A recent study by Koń and Jakubczyk (2019) suggests that, especially in the past, the disparity between WTP and WTA has been overestimated in the literature, for the presence of publication bias. In fact, it is the authors' opinion that in the past it was easier to get published for studies that suggested large differences between the two measures; on the contrary, studies finding similar WTA and WTP measures could be considered as less appealing and therefore less accepted, or even less submitted, for publication, thus being underrepresented in literature.

However, recent studies also confirm a disparity between WTP and WTA, such as Frondel et al. (2021), with a study based on supply security, although the authors find that the disparity reduces if the evaluation setting is perceived as more realistic. Koetse and Brouwer (2016), focusing on environmental goods, verify that a disparity between WTA and WTP does exist, increases with the distance from the reference point, and depends on the reference point itself. However, the authors conclude that "WTA values which are obtained from studies that assess a different range of possible changes, and that use a different reference value than is the case for the specific welfare analysis, may overestimate a welfare change" (p. 744). Furthermore, WTP could, instead, lead to underestimation issues. The authors suggest the need to rely on approaches specific to the considered case studies. In addition, Nguyen et al. (2021) sustain that "Many, perhaps most, interventions [...] appear disproportionately to be more likely to be regarded as remedial and therefore as reductions of losses rather than gains and, consequently, to call for WTA measurements" (p.631).

Weighing the two approaches (WTP and WTA), although the first is closer to a behavioural vision based on risk aversion, the second appears close to a more contingent logic and seemed therefore more suitable for setting up a survey designed for a sample of household users asked to evaluate a single interruption, which is likely to be intended as a welfare loss with respect to a service that is assumed to be continuous.

The choice of relying on WTA, in ESSENCE, appears therefore supported also in the light of subsequent contributions. First, it is advisable to frame the choice set properly, and WTA appears the most suitable indicator for a welfare loss such as a blackout, since WTP could lead to underestimating the damage. Second, the difference between the two measures could be less dramatic than expected. Third, our choice experiment evaluated exactly scenarios corresponding to the blackouts considered for the case studies, thus limiting the risk of overestimating the damage.

3 THE METHOD FOR THE ASSESSMENT OF THE COST OF THE BLACKOUT FOR NON-HOUSEHOLD USERS

As regards the second category of users, the "production function" approach was used. This approach, using data available at the macro level (for example, by industrial sector), is based on the measurement of the value added per unit of energy at industry level and, therefore, of the amount of the value of the load lost (VOLL) in the event of no energy supply due to the blackout. By multiplying the VOLL by the amount of energy lost, it is possible to provide an estimate of the industrial damage for the sector in question and for the economic system as a whole.

It's worth noting that estimations of blackout costs at the industrial level are prudential (or conservative) as they are based on the assumption of a linear relationship between energy consumption and production (simulations accounting for non-complete energy dependence are also provided). In reality, however, other sources of damage can affect the productive sector. Indeed, costs deriving from damage are of a diverse nature, and—besides loss of consumption goods—might include costs due to breakage of machinery or internal electrical lines, or costs for reactivation of lines, up to serious damages that make production lines unusable beyond repair.

4 DATA, RESULTS AND CONCLUSIONS

As regards the evaluation of the blackout cost for household users, our chosen methodology was implemented via a choice experiment. Within this framework, participants were presented with choice questions designed to elicit their willingness to accept (WTA) blackouts of predetermined durations, contingent upon a compensation from their electricity supplier in the form of a bill discount.

Recognizing the infrequent occurrence of such scenarios in typical residential settings, the questionnaire was meticulously structured to progressively familiarize respondents with the problem. This gradual introduction aimed to induce comprehensive reflection on the potential ramifications of an electricity interruption on household life. Regarding the core choice experiment component, respondents were directly queried on their acceptance or rejection of a specified blackout duration, provided a corresponding bill discount. Consequently, the choice sets were deliberately simplistic, comprising only two alternatives: 'Acceptance of the blackout given a certain discount' and 'No interruption and no discount'. Thus, each blackout scenario was characterized by two salient attributes: its duration and the proposed discount level.

A total of 28 distinct scenarios (representing combinations of duration and discount) were formulated, based on the following parameters:

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

The presentation of all 28 choices was deemed potentially burdensome, posing a risk to data quality and respondent engagement. To mitigate this, scenarios were randomly partitioned into 7 blocks of 4. Each respondent was subsequently exposed to only one randomly selected scenario from each block, resulting in a total of 7 scenarios per respondent.

Other variables of interest are: the age category, the gender, the income level, the education level, the zone type (if urban or non-urban) and the average monthly electricity bill.

Our analysis assumes that the probability of a respondent choosing a particular blackout scenario, and thus the associated utility, is a function of several key factors: the blackout characteristics themselves, the respondent and household characteristics.

For non-industrial users, the average cost of a 15-minute blackout is estimated at €2.86 for Italy. This figure varies, ranging from a minimum of €1.79 to a maximum of €3.34, depending on other user-specific attributes. As expected, the average cost increases significantly for longer outages; a 6-hour blackout results in an average cost of €43.04 for Italy (€62.65 for Poland), with a range between €32.43 (€35.31) and €54.57 (€73.46).

The results are similar in terms of order of magnitude but differ among the two countries. In addition, even in the same area, results are likely to change over time: Carlsson et al. (2021) find relevant WTP changes in two blackout evaluations of Swedish households carried on in 2004 and 2017 respectively (for instance, an unplanned outage of 1 hours showed a mean value 12.9 SEK in 2004 and 29.02 SEK in 2017; the same values are about 47 vs 107 SEK for 4 hours; the values are in constant 2017 prices).

As regards the determination of the VOLL for non-household users, the data used were the levels of value added at territorial level (from ISTAT source, up to 2008) and the data on distributed energy over the same period (from Terna, the Italian TSO). For Poland, the data on total gross value added were published by the Statistical Office in Warsaw, while data on total consumption were provided by the City of Warsaw, Infrastructure Department. The average VOLL calculated for the entire production system in Italy is 5.92 €/kWh (7.58 €/kWh for Poland). For comparison purposes, we can for example observe that these values are consistent with the results of Linares and Rey (2013) for Spain (5.56 €/kWh) or of De Nooij et al. (2007) for the Netherlands (7.59 €/kWh).

Notice that, for both case studies (Italian and Polish), the blackout characteristics were precisely defined in terms of lost load, time of the day, day of the week and duration. In addition, the blackout has been defined as unexpected. Both the methodologies adopted (stated preferences and production function approaches) are also able to differentiate the damage among user's types. We are therefore confident that all the relevant determinants later suggested by Ericson and Lisell (2020) have been accounted for, acknowledging that the estimation of damage at the industrial level is conservative as it does not account for non-linearities between energy consumption and production. With respect to the stated preference approach, the evaluation of damage is specifically referred to our case studies; however, as suggested by Frondel et al. (2021) and Carlsson et al. (2021), the results are often context-dependent (in temporal and geographical perspectives). Thus, for cost-benefit analysis purposes, we suggest relying on context-specific evaluations.

5 Bibliography

Abrate, G., Bruno, C., Erbetta, F., Fraquelli, G., & Lorite-Espejo, A. (2016). A choice experiment on the willingness of households to accept power outages. *Utilities Policy*, 43, pp. 151-164.

Angeletti, V., Guidi, L., Pestonesi, D., Biancardi, M., Alessi, M., Abrate, G., Bruno, C., Erbetta, F., Fraquelli, G., & Lorite-Espejo, A. (2014) *Italian Case Study: socio-economic impact* *analysis of a cyber attack to a power plant in an Italian scenario. Cost and benefit estimation of CIPS standard adoptions. A reduced version*. Ceris-CNR RT. 55. http://essence.ceris.cnr.it/images/documenti/RT_55.pdf

Bartoszewicz-Burczy, H., Bruno, C., García, F., & Włodarczyk, T. (2014). *Polish case study. Scenario based assessment of costs and benefits of adoption of comprehensive CIP standards*. Ceris-CNR RT. 56. http://essence.ceris.cnr.it/images/documenti/RT_56.pdf

Bruno, C., Abrate, G., Bartoszewicz-Burczy, H., Cortes, A., Diu A., Doheijo, E., Erbetta, F., Falavigna, G., Finardi, U., Fraquelli, G., Guidi, L., Lorite-Espejo, A, Moiso, V., Pestonesi D., Ragazzi, E., & Wlodarczyk, T. (2014). *Benefit analysis. Assessing the cost of blackouts in case of attack. Evaluation based on Italian and Polish case studies*. Ceris-CNR RT. 52. http://essence.ceris.cnr.it/images/documenti/RT_52.pdf

Bruno, C., Guidi, L., Lorite-Espejo, A., & Pestonesi, D. (2015). Assessing a potential cyberattack on the italian electric system. *IEEE Security & Privacy*, *13*(5), pp. 42-51.

Calabrese G., Finardi U., & Ragazzi, E. (2014). *Cost analysis of standard implementation in the SCADA Systems of electric critical infrastructures*. Ceris-CNR RT. 53. http://essence.ceris.cnr.it/images/documenti/RT_53.pdf

Carlsson, F., Kataria, M., Lampi, E., & Martinsson, P. (2021). Past and present outage costs – A follow-up study of households' willingness to pay to avoid power outages. *Resource and Energy Economics*, 64, 101216.

De Nooij, M., Koopmans, C., & Bijvoet, C. (2007). The value of supply security. The cost of power interruptions: economic input for damage reduction and investment in networks. *Energy Economics*, 29, pp. 277-295.

Diu, A. (2014). *Terms of Reference for the trials*. Ceris-CNR RT. 51. http://essence.ceris.cnr.it/images/documenti/RT_51.pdf

Ericson, S., & Lisell, L. (2020). A flexible framework for modeling customer damage functions for power outages. *Energy systems*, *11*(1), pp. 95-111.

Finardi U., Ragazzi E., & Stefanini, A. (2013). *Considerations on the implementation of SCADA standards on critical infrastructures of power grids*. Ceris-CNR RT. 47. http://essence.ceris.cnr.it/images/documenti/RT_47.pdf

García F., Alessi M., Bartoszewicz-Burczy, H., Cortes A., Pestonesi D., & Włodarczyk, T. (2013). *Attack scenarios. Threats, vulnerabilities and attack scenarios along with their selection criteria*. Ceris-CNR RT. 48. http://essence.ceris.cnr.it/images/documenti/RT_48.pdf

García Gutiérrez, F., & Ragazzi, E. (2014) *Trial evaluation: conclusive lessons from Essence case studies*. Ceris-CNR RT. 57. http://essence.ceris.cnr.it/images/documenti/RT_57.pdf

Kahneman, D., Knetsch, J.L., & Thaler, R.H. (1991). Anomalies: The endowment effect, loss aversion and status quo bias. *The journal of economic perspectives*, *5*(1), pp. 193-206.

Koetse, M.J., & Brouwer, R. (2016). Reference dependence effects on WTA and WTP value functions and their disparity. *Environmental and Resource Economics*, 65, pp. 723-745.

Koń, B., & Jakubczyk, M. (2019). Is the literature on the WTP-WTA disparity biased?. *Journal of Behavioral and Experimental Economic*s, 82, 101460.

Frondel, M., Sommer, S., & Tomberg, L. (2021). WTA-WTP disparity: the role of perceived realism of the valuation setting. *Land Economics*, *97*(1), pp. 196-206.

Linares, P., & Rey, L. (2013). The cost of electricity interruptions in Spain. Are we sending the right signals? *Energy Policy*, 61, pp.751-760.

Nguyen, K.T., Knetsch, J.L., & Mahasuweerachai, P. (2021). WTP or WTA: a means of determining the appropriate welfare measure of positive and negative changes when preferences are reference dependent. *Environmental and Resource Economics*, 78, pp. 615-633.

Ragazzi E., & Stefanini A. (2019), Are security standards for electricity infrastructure a good choice for Europe? Evidence on cost and benefits from two case studies. *International Journal of Critical Infrastructures*, *15*(3), pp. 206-226.

Reichl, J., Schmidthaler, M., & Schneider, F. (2013a). The value of supply security: the cost of Power outages to Austrian households, firms and the public sector. *Energy Economics*, 36, pp. 256-261.

Reichl, J., Schmidthaler, M., &Schneider, F. (2013b). Power outage cost evaluation: reasoning, methods and application. *Journal of scientific research & reports*, *2*(1), pp. 249-276.