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True cost of electric service: What reliability metrics alone fail to communicate☆

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A B S T R A C T

Valuing electric power, particularly its loss within the residential sector, has historically been a great challenge that many researchers have undertaken without reaching a consensus. Electric power can be troublesome to appraise because consumption is not the customer's main goal, but rather a means to achieve a desired good or service that often has unquantifiable personal value. This paper proposes a market-based household production method that quantifies the customer electric service interruption costs in the residential sector. Because an individual's personal time is necessary to replace services owing to the lack of electric power, we propose a method that estimates the weighted market cost of a person's time in accordance with their occupation to better calculate customer outage costs. We also present a macroeconomic production method to estimate losses in the residential sector. Finally, we propose a method for calculating the true costs of electric services by factoring the outage costs with the electrical utility rate to be analyzed using reliability metrics. The proposed approach facilitates a closer estimation of the low-bound true costs of utility-supplied electrical services for consumers who have not taken mitigation measures, serving as a warning for energy regulators to impose corrective actions or appropriate penalties on unreliable utilities and/or as an indicator for customers to invest in alternative energy sources.

1. Introduction

Access to electrical power in the modern day has facilitated the acquisition of goods and services that would otherwise be more expensive to obtain through alternate means. Social and private investment in electrical infrastructure is ultimately justified because it reduces the amount of work, time, and costs that people must incur to obtain these goods and services, of which several can be lifesaving. Our reliance on electricity to power different services and businesses also makes us vulnerable to cascading infrastructure failure, which may result in higher rates of human mortality when electric power is interrupted for long periods. Long power outages may result from major events, such as the "energy insufficiency-caused power crisis" triggered by the extreme winter storm in Texas (Guanglun et al., 2022; Hebner, 2021; Petitet et al., 2022) or the longest power blackout in the world suffered in Puerto Rico after Hurricanes Irma and Maria (Castro-Sitiriche et al.,

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2018; Humphery, 2023). In both cases, natural disasters, in combination with previous human-made decisions, led to long-term power outages with dire consequences (Kishore et al., 2018; Kwasinski et al., 2019; Lopez-Cardalda et al., 2018).

While it could be argued that electric utility grids are built to provide day-to-day electric services and not necessarily to withstand major events, human decisions prior to such major events should be placed under tighter scrutiny, because poor public policy and utility management decisions may either fuel or be the main cause of widespread electric outages (Madani and Novosel, 2005). The major blackout that affected the U.S. northeastern grid in 2003 identified the lack of grid maintenance from an interconnected Ohio power utility, along with diminishing year-by-year reserve capacity, prompting the belief that "the grid had been designed and managed for one purpose (reliability) but used for another (economy)" (Madani and Novosel, 2005). Although it would be improper to hold electric utilities accountable for the occurrence of natural disasters, they should be liable for lax power grid reliability metrics and low levels of resilience to major events because of poor policy and management decisions (Puerto Rico Electric Power Authority PREPA, 2023).

Prior to the passage of Hurricanes Irma and Maria, official Puerto Rico Electric Power Authority (PREPA) public utility data suggested that the reliability of Puerto Rico's electrical power grid may have been compromised for economic reasons (Puerto Rico Electric Power Authority PREPA, 2023). More data may be necessary to fully ascertain this suggestion; however, PREPA was already under U.S. congressional scrutiny because of the Puerto Rican government's chronic financial woes before the hurricanes (Congress, 2023). Fig. 1 illustrates how the utility's rising contractual obligations corresponded with a declining employee headcount, shrinking warehouse inventory, and a reduction in both capital improvements and maintenance expenses, which consequently correlated with the rising trend of minutes per electric service interruption. The months before Hurricanes Irma and Maria impacted Puerto Rico in September 2017, PREPA's employee headcount, warehouse inventory, and both capital improvements and maintenance expenses had decreased by 2981 employees, $60 million, and $313 million dollars, respectively, compared to those in June 2009. Customer minutes per interruption were conversely on the rise, with a study claiming that the total customer outage minutes were 300% higher in the year after both hurricanes (Nassif et al., 2022).

Ignoring grid reliability and resilience metrics comes at a price that is ultimately paid by customers, who must suffer electric service interruptions from the vulnerable and unreliable power grid of an unaccountable utility. In Puerto Rico, after extensive research and promising federal and local governmental action post Hurricanes Irma and María, there was still a lack of progress and accountability in the electric grid's restoration and hardening efforts, as evident in Fig. 1, which was further proven by the human and financial toll suffered from Hurricane Fiona's impact on the island's infrastructure in September 2022 (U.S. Government Accountability Office GAO, 2022). The reliability of Puerto Rico's electric power grid did not improve after the U.S. Congress imposed the Financial Oversight and Management Board (FOMB) and the Puerto Rican Government relinquished the operation and maintenance (O&M) of PREPA's transmission and distribution (T&D) system to a private concessionaire known as LUMA Energy (LUMA) in June 2021 (Kunkel and T. Sanzillo, 2021; Puerto Rico Energy Bureau, 2023).

Lack of accountability appears to play a key role when reliability and resiliency metrics are ignored or even misunderstood by regulating entities. The Dutch Energy Regulator sets a clear example of the economic consequences of electric utility service unreliability by having utilities reimburse affected customers through market-like incentives based on the (perceived) costs of power outages; as such, the level of grid reliability is far superior to that of other states within the European Union (Baarsma and Hop, 2009). Applying economic consequences to unreliable utilities may seem favorable, but regulating perceived power outage costs or achieving consensus at the residential customer scale, as opposed to commercial and industrial customers, can prove to be difficult. A particular power outage will affect each customer differently, some more than others, depending on the type of interruption, the customer's profile, and the value that the customers give to the services

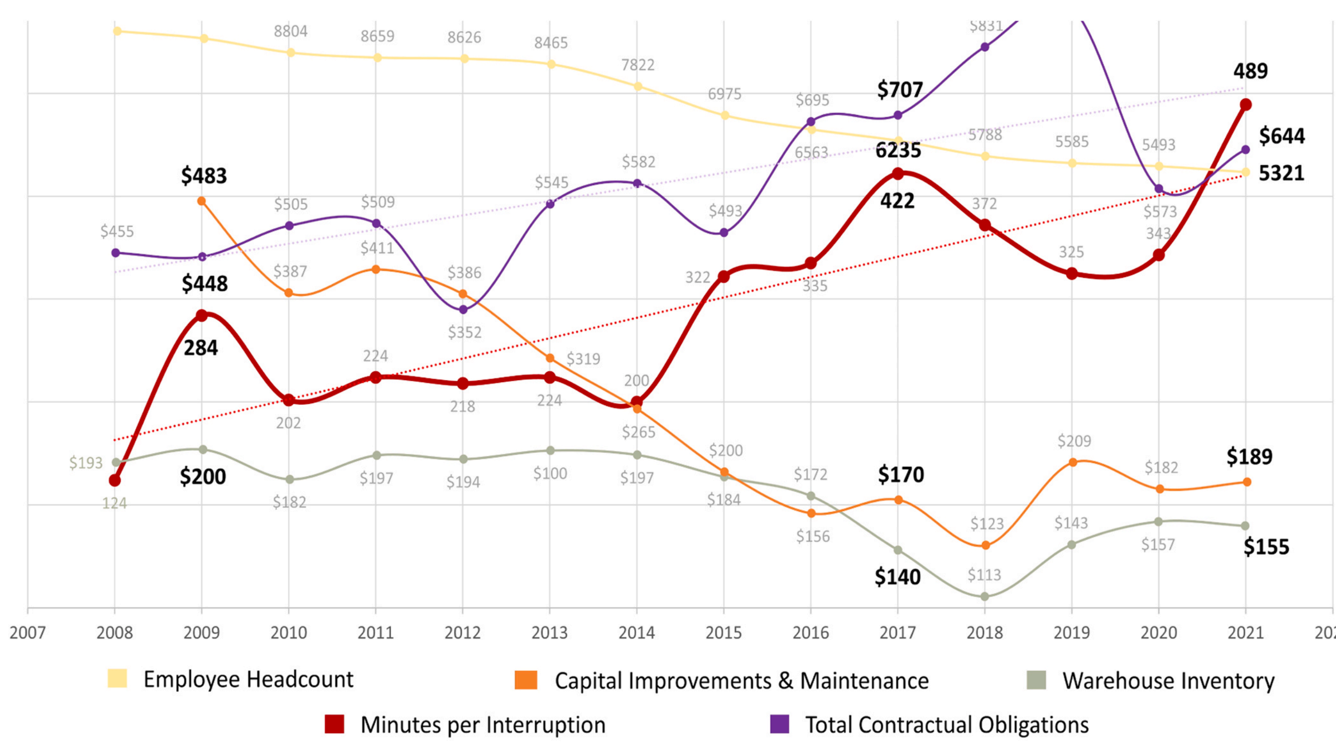

Fig. 1. Correlation between time per electric service interruption and number of employed personnel, warehouse inventory (in millions), capital improvements & maintenance expenses (in millions), and total contractual obligations (in millions) (Puerto Rico Electric Power Authority PREPA, 2023). As total contractual obligations increased, personnel, inventory, improvements, and expenses were reduced, with minutes per interruption consequently rising.

or commodities that they must now acquire through other means (Gorman, 2022).

Because the value of power will ultimately be defined by each individual customer's end-use of electricity, it will be characterized or based on their individual wants and needs while being constrained by their income (Munasinghe, 1980a), regardless of socioeconomic class, tier, or status (Fouquet, 2014). Customers do not really want quantifiable amounts of electricity in and of themselves (Kalt et al., 2019), nor do they have any use for the carriers through which electrical current flows (Miller et al., 2018). Energy use alone does not contribute to meeting customer needs or providing well-being, unless it is a means of acquiring specific services, including goods or commodities that demand electric power as an input (Kalt et al., 2019). Because each customer wants to acquire a specific type of service or good at a time and frequency of their choosing or they are able to afford, not having access to these services because of electric power interruptions would ultimately affect the customer's satisfaction and requirements for compensation and also contribute to load defection resulting from renewable energy system (RES) acquisition (Should I Stay, 2020; Haapaniemi et al., 2018).

Understanding the costs that residential-scale customers must incur when seeking goods or services that require electricity in the absence of electric power should provide an initial glimpse of the *true costs of electric service* and the value that this service adds to our daily lives. The *societal economic cost of electric service unreliability* must be examined indirectly by utilizing the economic principle of substitution, where the cost of replacement is used to measure the initial value of access to electric services (Billinton et al., 1991). The problem with estimating societal economic cost is that there is disagreement in its quantification at the residential scale between past and present investigations (Gorman, 2022). Researchers have employed different terms and methods to describe the same concept throughout the years, from interruption costs (Billinton et al., 1991), to outage costs (Munasinghe, 1980a; Sanghvi, 1982), customer interruption costs (Küfeoğlu and Lehtonen, 2015a), opportunity costs of unsupplied power (Hashemi et al., 2018), opportunity costs (in relation to lost time) (Spierre Clark et al., 2023), marginal costs of unsupplied electricity (Bental and Ravid, 1982), and value of lost load (VoLL) (Gorman, 2022; London Economics International LLC, 2013; Siemens Industry, 2019a), to cite a few examples.

In this paper, we employ the *customer electric service interruption cost* (CESIC) as an umbrella term to describe residential-scale electrical power outage costs for two reasons. The first is to differentiate electric service interruption costs from other types of customer service interruption costs, such as those related to gas or water, when the absence of electric power is not the cause of interruption. The second reason is to provide a simple, unified term that is both meaningful and practical. For example, some employ the "marginal costs of unsupplied electricity," but misunderstandings can ensue just by using the term "marginal costs" because it could suggest that costs are being incurred to augment production or electricity interruptions to be traded, when there is no market that trades lost electric service (De Nooij et al., 2007), with a similar argument being presented with opportunity costs of unsupplied electricity. Hence, we employ the CESIC for residential sector outage cost estimation and define it as the sum of the direct costs of services and goods lost because of electric service interruption, time costs incurred by customers replacing goods and services through other means, mileage costs (if motor vehicles are needed to replace these goods and services), and the subjective valuation that each individual may assign to an electric service. We also provide an adapted macroeconomic production function.

Proper hourly CESIC calculations will not only yield a more precise VoLL but can be used to estimate annual outage costs to uncover the true costs of electric services or the overall costs of supplying electric services. The true costs are the ratio of the sum of the annual costs paid at the utility rate plus the annual costs of not having energy divided by the difference in the average annual consumption minus the average avoided consumption. In a reliable electric power grid, the costs of not having energy should be close to zero, with a true cost equal to the utility rate; however, in areas of poor electric service reliability, properly quantifying the costs of not having electricity will reveal the value of having access to a reliable electric utility power grid. Both the CESIC and, consequently, the true costs of electric services can be used to measure the degree of inequity and injustice present in unreliable electric services, with the latter serving as a benchmark comparison when evaluating the levelized costs of alternative energy sources, instead of simply observing the utility's electric service rate. Because of Puerto Rico's historical electrical reliability and resilience issues, we propose a methodological framework that quantifies the impact of power outages on households, with the hope that it can become a message for regulators and policymakers toward equity and energy justice, which current reliability and resilience metrics alone are not communicating.

2. Literature review

2.1. Need for the redefinition of power outage costs in Puerto Rico

When assessing the reliability of an electric power grid, certain metrics are commonly evaluated, such as the System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), and Customer Average Interruption Duration Index (CAIDI). The SAIDI indicates the total duration of an electric service interruption for a specific utility-defined period, typically monthly or annually; the SAIFI indicates how often the average customer experiences sustained interruptions over the specified period; and the CAIDI represents the average amount of time required to restore lost electric service within the specified time reference (The Institute of Electrical and Electronics Engineers IEEE, 1998). Electrical resilience is typically measured by the ability of a system to respond to and recover from major events (Ashrafi and Parhizkar, 2023). Quantifying the number of customer hours of lost electric service (CHoLES) and the rate at which it increases after a major event is one method of measuring resilience (Castro-Sitiriche et al., 2018).

In LUMA's first-year quarterly reports submitted to the Puerto Rico Energy Bureau (PREB), the SAIDI, SAIFI, and CAIDI metrics greatly surpassed the reliability metrics of similarly islanded grids in the state of Hawaii (U.S. Energy Information Administration EIA, 2023a) and all of the mainland U.S. utilities (U.S. Energy Information Administration, 2023), as shown in Table 1. Only three other mainland U.S. utilities surpassed LUMA's SAIDI when major events were excluded. LUMA operated without the burden of PREPA's contractual obligations and with a greater warehouse inventory but had an even further reduced employee headcount of 3363 (of which 47% provided line and substation maintenance), which corresponds with the unsurprisingly poor reliability metrics (Puerto Rico Energy Bureau, 2022). The importance of highlighting employee headcount is that an optimal number of employees is required for cost-efficient day-to-day operations. A higher number of employees than needed translates into unnecessary payroll expenses and added occupational health and safety liabilities for the utility. A lower-than-optimal number of employees would be overburdened by an excessive workload that would ultimately compromise the utility's efficiency and reliability, especially in complex power grids such as those in Puerto Rico.

It appears that poor reliability metrics and the frequency of devastating faults with high restoration times for both PREPA and LUMA, as shown in Fig. 2, were not sufficient to convey a message to the PREB or local policymakers. The question now concerns the definition and quantification of locally employed residential-scale outage costs. In 2019, the PREB commissioned PREPA to provide an Integrated Resource Plan (IRP) that included estimates of outage-related economic losses using survey data obtained from the mainland U.S. and other countries (London Economics International LLC, 2013; Siemens Industry, 2019b; Sullivan et al., 2023) and through estimates provided by the Lawrence

Table 1
Comparison of the Reliability Metrics of Puerto Rico, Hawaii, and Mainland U.S.

Reliability Metric	PREPA/LUMA June 2021 – May 2022 (No Major Events Recorded)	Hawaii (All Events)	Hawaii (Not Including Major Events)	Mainland U.S. (All Events)	Mainland U.S. (Not Including Major Events)
SAIDI (Hours)	27.44	3.12	1.77	5.69	2.44
SAIFI (Interruptions)	7.5	1.65	1.2	1.72	1.29
CAIDI (Hours)	3.72	1.9	1.48	2.66	1.75

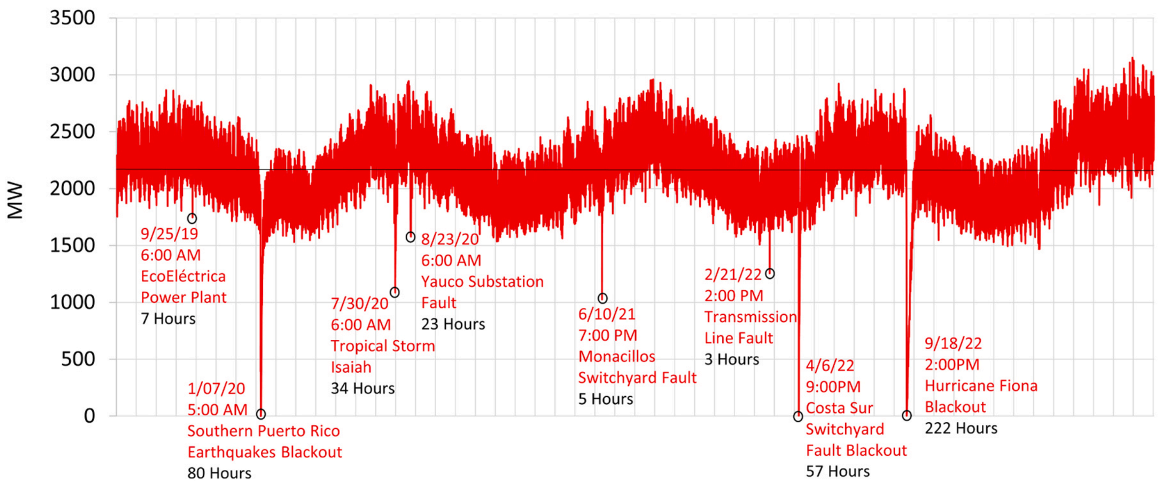

Fig. 2. Puerto Rico power consumption from June 2019 to June 2023, highlighting blackouts caused by Hurricane Fiona and other non-major events, with the number of hours taken for full electric service restoration (Siemens Industry, 2019a).

Berkeley National Laboratory's Interruption Cost Estimate (ICE) Calculator (Nexant, 2023a). Lacking local survey data, Siemens' team initially chose New Zealand as the country whose system-wide conditions were the most similar to those of Puerto Rico, adapting their survey-based VoLL estimations to match our profile. Despite a higher median income, New Zealand has a lower cost of living than the U.S. and is similar to San Juan, Puerto Rico (LivingCost.org, 2023). Using their adapted method, the Siemens team estimated a VoLL of $12.27/kWh. On a second approach, estimates were obtained through the ICE calculator, where Puerto Rico was not even listed as an option within the application's website (Nexant, 2023a), whereas the state of Hawaii was used in the PREPA IRP (Siemens Industry, 2019b). The state of Hawaii's median income is over four times greater than Puerto Rico's and its cost of living is 1.3 times greater on average. Again, it is an unfair comparison, with a questionable $4.04/kWh VoLL outcome.

The drawback of both approaches was that the evaluated survey and macroeconomic data corresponded to states and countries whose median income was greater than that of Puerto Rico (World Bank Group, 2023). This should come as no surprise, as Puerto Rico has the lowest median income compared to those of all 50 U.S. states, the District of Columbia, Guam, and the U.S. Virgin Islands (Division of Occupational, 2022). It is important to highlight that both the median income and cost of living are important and unmentioned factors in the VoLL estimations made for New Zealand and Hawaii. The former was based on residential and non-residential willingness-to-pay (WTP) surveys, which is explained more in detail later (London Economics International LLC, 2013), whereas the latter used surveys that "are 20+ years old," whose use was "not appropriate for estimating costs of wide-spread, long-duration (>24 h) interruptions", and its data "is not statistically-representative for all regions of the U.S." (Nexant, 2023b).

Research has demonstrated that customers who earn a greater income are more likely to consume more energy and are willing to pay more to avoid suffering from an electric outage (Munasinghe, 1980b). This is not perceived in the IRP, which considers residential customers as single clients when each customer belongs to a household with multiple consumers. Puerto Rico's households shelter up to 2.8 members on average, and each member ultimately affects the VoLL differently, as our research suggests (Table 9). It is uncertain whether the PREB considers the observations and inadequacies described above, but customer outage cost calculations must be properly understood and consequently revised. Improper outage cost estimation or its lack of detail may obscure the need for corrective action in the most vulnerable communities of the island, particularly when resources are scarce owing to congressionally imposed austerity measures. Revision is necessary if the utility is to be properly held accountable for underinvesting in susceptible sectors and for massive power outages during non-major events such as those highlighted in Fig. 2.

Furthermore, the overall electricity consumption did not increase in tandem with the additional 21,000 residential customers that Puerto Rico registered in the past two years (Puerto Rico Energy Bureau, 2022). Instead, there is a rising trend in RES acquisition, as shown in Fig. 3, which could be interpreted as an aftereffect of high levels of grid unreliability. The average installation sizes of installed photovoltaic (PV) and distributed energy storage systems (DESS) seem to be larger than what research has estimated to be necessary for 51% of all Puerto Rican households (Castro Sitiriche, 2019). According to their consumption, they require less than 4.4 kW of installed PV, with 25% requiring less than 2.2 kW. If higher income corresponds to higher consumption and willingness-to-pay (to avoid suffering an electrical power outage) (Munasinghe, 1980b), we can deduce that low-to-medium income households may not purchase, finance, or otherwise acquire RESs owing to the average installation size reported by LUMA.

The probability that Puerto Rican low-to-medium-income households do not have access to RES acquisition makes sense when considering that the island's economy is subject to the mainland U.S., where the minimum sustainable price (MSP) for PV installation is approximately $2.55 per watt of installed PV and the modeled market price (MMP) is $2.95 per watt of installed PV (Ramasamy et al., 2022). At these prices, the average size of stand-alone installed PV in Puerto Rico would end up costing between $14,700 and $17,100, and the added

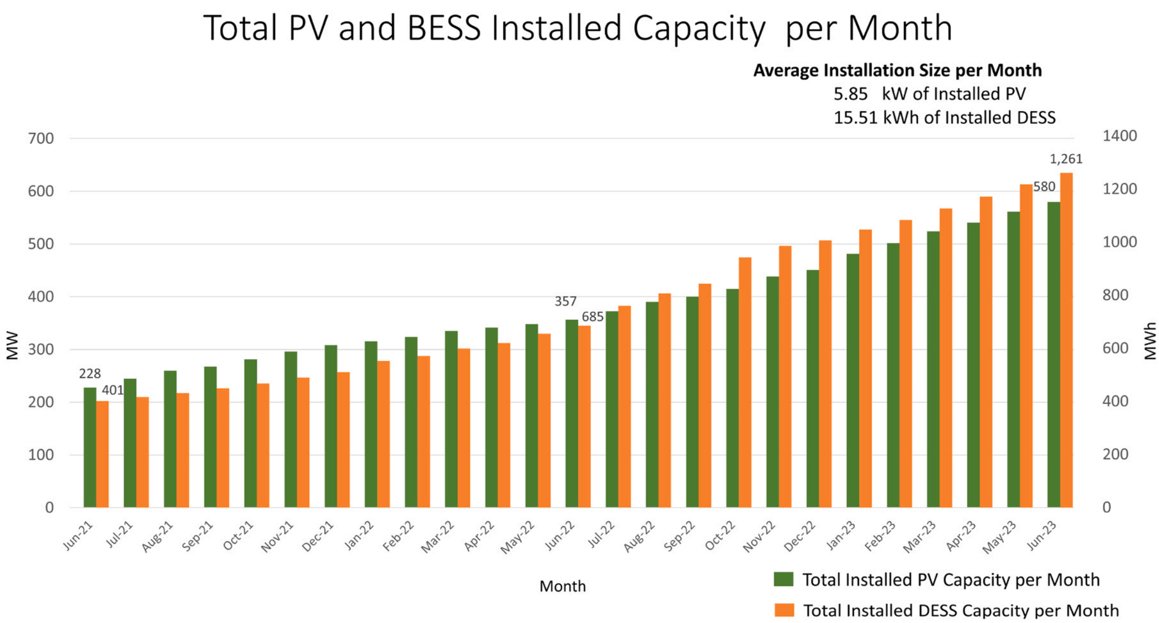

Fig. 3. Total PV and BESS installed capacity per month, highlighting the average installation size per site from June 2021 to June 2023.

storage costs could easily increase this beyond the $33,858 benchmark. Bureau of Labor Statistics data places Puerto Rico with the lowest median income of all U.S. states and territories at an annual $23,480 or $11.21 per hour (Bureau of Labor Statistics, 2023a), with a 44.9% poverty rate, which is double the Mississippi poverty rate of 24.2% (La Salle Academy, 2023).

Thus, it is evident that many Puerto Rican households may not afford to finance an RES to avoid being impacted by power outages. Outages burden vulnerable households with lost services and goods, reduce replacement costs, and force sacrifices of time and other resources to undertake these replacements. In our work, we quantify how low-to-medium-income households are most susceptible to unreliable electric service costs. However, before we can understand the different methods that have been historically employed to estimate outage costs, we must emphasize those employed in the residential sector.

2.2. Defining outage costs

To define the CESIC, we use descriptions or definitions of outage costs found in the literature. Researchers have established that interruption costs are indicators that quantify the economic consequences of electric service interruptions, which can then be used to estimate the value of maintaining the continuity of the power supply through the economic principle of substitution (Schröder and Kuckshinrichs, 2015) and ensure social benefits via outage mitigation costs (Gorman, 2022). Interruption costs can be classified as all the direct and indirect costs that industries, commerce, communities, and/or individuals must incur during a power outage (Billinton et al., 1991; Gorman, 2022).

Outage cost estimates must be accounted for in detail because they vary depending on several factors (Gorman, 2022), such as the type of impact, timing, and duration of the outage, frequency of interruptions, customer profile type (as different customers may value electric services or associated costs differently), and the weighting of methods used to quantify costs (London Economics International LLC, 2013). Whether the interruption is partial or complete, localized or widespread, and planned or unplanned will all have different impacts and costs (Billinton et al., 1991; De Nooij et al., 2007). In some regions, even the season in which an interruption occurs produces different interruption costs (Sanghvi, 1982).

Direct costs result from service interruptions that have a direct impact from an economic or social perspective (Billinton et al., 1991). Loss of production, restart costs, spoiled food and medicine, damaged materials or lost data, injury, or loss of life can be classified as direct economic impacts, whereas the loss of satisfaction or well-being, leisure time, or inconveniences that affect well-being, such as loss of transportation or uncomfortable building temperatures, can be considered direct social impacts. Indirect costs are difficult to quantify because they tend to be secondary consequences that sometimes defy strict categorizations as solely economic or social impacts. Examples include economic costs resulting from civil disobedience, evacuation due to safety device failure, crime during a blackout, or future outage mitigation costs, such as those incurred in business relocation, procurement of backup power generators, protective equipment, and/or other grid-hardening investments (Billinton et al., 1991; Gorman, 2022).

When characterizing or defining customer profiles affected by a power outage, the type, class, or customer sector should be identified along with the description and operational size of the activities and/or services that are unmet owing to the electric utility service interruption and how their dependency on electric power can shift according to the time of day and season (Billinton et al., 1991). The perceived level of impact will also be influenced by customer attitudes toward the power interruption and the degree to which they prepare themselves for grid power outages, making the need for preparatory actions an inversely proportional function to the level of service reliability and grid resilience (Billinton et al., 1991). Advance warning of a potential outage can reduce the cost of certain activities owing to rescheduling, among other mitigation measures that could be taken (Sanghvi, 1982). The level of preparedness may lower the time and frequency at which customers experience outages, helping to distinguish household or customer outages from grid outages. Although customer preparedness depends on the level of reliability of tge electric utility service, it also depends on income regardless of customer class, evidencing the relationship between income and energy service price elasticities (Fouquet, 2014).

Typically, the electric service industry divides customer classes or types into residential, commercial, and industrial. The local Puerto Rican utility further differentiates sectors by adding public lighting, agriculture, and other agency classes, which we do not cover in this study. As mentioned, each class will be impacted differently, directly and indirectly, although mitigation costs may differ from class to class. In the industrial and commercial sectors, direct costs from losing electric power can be classified as the opportunity cost of idle resources, production delays, equipment damage, data loss, and occupational employee health and safety. Indirect costs include delayed deliveries in the value chain, damage to consumers who purchase the company's products, and cost/benefits for some manufacturers (Sanghvi, 1982; Schröder and Kuckshinrichs, 2015). Mitigation costs include emergency generator procurement, battery energy storage systems, and investments in grid construction via special tariffs (Hashemi et al., 2018; Bental and Ravid, 1982; Schröder and Kuckshinrichs, 2015).

2.2.1. Outage cost considerations for the residential sector

There is much disagreement on how to quantify outage costs in the residential sector. Some researchers argue that household losses are reduced to forgone leisure, whose value is equal to income per hour (Billinton et al., 1991; Munasinghe, 1980a; Becker, 1965; Caves et al., 1990), and fail to acknowledge household activities as lost production of services. Other researchers argue that households should be treated as centers of production because they produce welfare with goods and time (Gilmer and Mack, 1983; De Nooij et al., 2007). Electrical service interruptions restrict activities such as leisure and work, and in some cases, sleep time is lost, generating stress that can have a cascading impact on mental and physical health and affect well-being (Spierre Clark et al., 2022). Property damage, data loss, food spoilage, or direct health impacts for individuals who rely on medical equipment, refrigeration for medicine, insulin, etc., can also result from electric service interruptions (Schröder and Kuckshinrichs, 2015; Munasinghe and Sanghvi, 1988; Spierre Clark et al., 2022).

Well-being tends to be a concept particular to the residential sector, which is elusive and difficult to quantify directly because of the diverging definitions that each customer may have. Although attempts have been made to detect and understand how energy use can contribute to human welfare, there is no consensus that defines the quality and scope of many electric services that improve the quality of life (Kalt et al., 2019; Brand-Correa et al., 2018). This is not without pitfalls, as both under- and over-usage of energy can work against human welfare before even considering the higher electric bills.

Excess usage of electric energy will not necessarily improve living standards but instead prove detrimental to human well-being (Castro-Sitiriche and Ozik, 2014; Ortiz et al., 2021), especially if it curtails the satisfaction of other needs or limits social integration (Brand-Correa et al., 2018). For example, the use of electric power can provide illumination for work after sunset, and television can provide leisure, but overusage could affect sleep patterns and result in other mental health issues. Conversely, superfluous power consumption in some areas does not compensate for the lack of other required services. Excess lighting does not provide refrigeration required to conserve perishable foods and medicines.

According to Sitiriche and Ozik, understanding how under- and overusage of energy can indicate energy poverty and/or affluence is a priority (Castro-Sitiriche and Ozik, 2014). They examined how improved access to electric energy positively affects human well-being and identified how the complex dynamics between the drivers of well-being and human development creates a feedback loop that ultimately improves access to electricity. This study provides a quantitative approach that warns against excess power utilization and under-consumption (such as those from power interruptions) as parameters that reduce human satisfaction (Ortiz et al., 2021).

While one team of researchers introduced the concept of the Energy Service Cascade as a means to better understand the relationship between energy and customer well-being (Kalt et al., 2019), another team proposed to study the relationship between human needs and the energy services that could satisfy them via Max–Neef's Human Scale Development (HSD) classification of human needs (subsistence, protection, affection, etc.) (Brand-Correa et al., 2018). These approaches are similar to Sen and Nussbaum's capability theory, where to achieve basic capabilities (good health, social respect, education, etc.), a number of secondary capabilities are required (washing, cooking, accessing information, etc.), some of which demand energy services (lighting, space, heating, refrigeration, etc.) that, in turn, require an energy supply and ultimately fuel (Spierre Clark et al., 2023; Day et al., 2016).

Because the valuation of the ultimate end use of energy varies from person to person, it is important to define or characterize how the loss of power indirectly impacts households by restricting the acquisition of goods, services, and other utilities (water, refrigeration, cooking food, etc.) because this forces consumers to seek replacements, requiring more time, and perhaps even incurring travel and fuel expenses (Schröder and Kuckshinrichs, 2015; Sandia National Laboratories, 2018). Restriction of goods and services also impacts the local economy by limiting per-capita personal consumption expenditures (PCE). Both the loss of leisure time and sleep time directly impacts performance (Slimani et al., 2018; Fucci et al., 2020), and hence impacts productivity and value, indirectly costing employers. As in the industrial and commercial sectors, residential sector customers may incur mitigation costs such as those from emergency generator procurement, renewable energy generation, and/or battery energy storage systems (Schröder and Kuckshinrichs, 2015).

2.3. Methods of evaluation

Methods for evaluating interruption costs are indirect, with no universally adopted method (Billinton et al., 1991). Among the various approaches, researchers have historically relied on surveys, demand curve estimations based on consumer surplus measures, case studies of actual blackouts, and production function analysis (Billinton et al., 1991; Gorman, 2022; London Economics International LLC, 2013; Caves et al., 1990). Table 2 lists various evaluation methods, with particular emphasis on the final three production function methods proposed in this study.

2.3.1. Survey Methods

Surveys are the most commonly employed method for evaluating the economic value of power interruptions (Küfeoğlu and Lehtonen, 2013). Many researchers believe that customers can better assess their economic losses due to electric power interruptions, although some respondents may intentionally or unintentionally provide misleading or exaggerated answers (Küfeoğlu and Lehtonen, 2015a). Many residential sector respondents do not have a complete idea of the expenses they incur when replacing services and goods lost to power interruptions, sometimes reporting higher economic losses than the costs calculated by lost value-added methods or yielding unreliable answers associated with either their WTP to avoid suffering a power interruption or willingness to accept (WTA) compensation for an enduring outage or less service reliability (Billinton et al., 1991; Küfeoğlu and Lehtonen, 2015a; Caves et al., 1990).

It must be noted that a given customer's WTP is constrained by their income and consumption level (Gorman, 2022; Munasinghe, 1980a; Schröder and Kuckshinrichs, 2015), although some customers may require higher compensation than what they are willing to pay (Caves et al., 1990). Some customers do not require compensation or are unwilling to pay to avoid interruptions during specific seasons of the year, regardless of historical reliability issues within their electric power grid (Cohen et al., 2016).

Therefore, surveys tend to exhibit a large range of outage cost estimates depending on the location and customer class. Improper survey wording can also result in distorted responses (Schröder and Kuckshinrichs, 2015). To reduce errors, it is recommended that surveys be pretested for representativeness and adjusted for both extreme outliers and potential bias reduction, as well as to ensure that the questions are both understandable and answerable in a useful fashion (London Economics International LLC, 2013).

2.3.2. Demand and case study methods

The demand curve method measures consumer surplus and WTP for demand by revealing how a customer's activities depend on electricity

Table 2
Methods of Evaluation.

Survey Methods	Demand and Case Methods	Production Function Methods
Direct Costing (Should I Stay, 2020; Bureau of Labor Statistics, 2023a; Schröder and Kuckshinrichs, 2015; Slimani et al., 2018; Küfeoğlu and Lehtonen, 2015b)	Demand Curve Method (Should I Stay, 2020; Puerto Rico Energy Bureau, 2023; Haapaniemi et al., 2018)	Revealed Preference (Spierre Clark et al., 2023; Bureau of Labor Statistics, 2023a)
Stated Choice Surveys (Should I Stay, 2020; Puerto Rico Energy Bureau, 2023; Baarsma and Hop, 2009; Bureau of Labor Statistics, 2023a; Schröder and Kuckshinrichs, 2015; Fucci et al., 2020)	Case Studies (Spierre Clark et al., 2023; London Economics International LLC, 2013; Bureau of Labor Statistics, 2023a)	Cost of Back-Up Generation Method (Hashemi et al., 2018)
Contingent Valuation Method (CVM) (Should I Stay, 2020; Spierre Clark et al., 2023; Schröder and Kuckshinrichs, 2015)		Price of Electricity Method (Puerto Rico Energy Bureau, 2023; Schröder and Kuckshinrichs, 2015)
Contingent Ranking Method (CRM) (Spierre Clark et al., 2023; Schröder and Kuckshinrichs, 2015)		Ratio of Production Output to Electricity Consumption (Hashemi et al., 2018; Schröder and Kuckshinrichs, 2015)
		Macroeconomic Production Function (Puerto Rico Energy Bureau, 2023; Billinton et al., 1991; Spierre Clark et al., 2023; Bureau of Labor Statistics, 2023a; Slimani et al., 2018; Küfeoğlu and Lehtonen, 2013)
		Household Production Method (Schröder and Kuckshinrichs, 2015; Becker, 1965; Ortiz et al., 2021)
		Forgone Leisure / Wage Rate Method (Puerto Rico Energy Bureau, 2023; Baarsma and Hop, 2009; Haapaniemi et al., 2018; Spierre Clark et al., 2023; La Salle Academy, 2023; Schröder and Kuckshinrichs, 2015; Day et al., 2016; Sandia National Laboratories, 2018; Válek and Jašíková, 2013; Lehtonen and Lemstrom, 1995)

using the measured or estimated time-of-day pattern of electricity consumption, constrained by income and the daily rhythm of activities, among other factors (Billinton et al., 1991; Gorman, 2022; Sanghvi, 1982). The case study method is used to evaluate the interruption costs of an actual event instead of a hypothetical event (London Economics International LLC, 2013; De Nooij et al., 2007; Schröder and Kuckshinrichs, 2015). Adding estimates of residential sector interruption costs would add more depth to case studies exploring bottom-up grid transformations in response to catastrophic events with long blackouts.

2.3.3. Production function methods

Production functions or proxy methods estimate outage costs by relying on proxies, that is, substitutes or indirect means, to estimate the damages and inconvenience costs incurred by customers during electric power interruptions (London Economics International LLC, 2013; Caves et al., 1990). For example, although the revealed preference method was identified as a survey in one source of literature (London Economics International LLC, 2013), this is essentially a production function method that derives outage costs by observing household or company investments to avoid electric service interruptions (Schröder and Kuckshinrichs, 2015). The cost of the backup-generation method involves the use of backup generators until the levelized cost of the additional backup power equals the power outage interruption costs in $/kWh (Bental and Ravid, 1982). The retail price or rate of electricity method calculates the low-bound costs of electric service interruptions, as it represents the cost of forgoing a production increment, but fails to measure the intramarginal demand losses and does not consider customer valuation of electricity (Gorman, 2022; Caves et al., 1990). The method concerning the ratio of output to electricity consumption, or what a business produces by its electricity consumption, establishes upper-bound outage cost estimates, assuming there is no substitution between electricity and other factors of production, lost production is not recovered, and costs of damaged equipment and materials are ignored (Bental and Ravid, 1982; Caves et al., 1990).

2.3.4. Macroeconomic production function

The macroeconomic production function (MPF) is a variation of the ratio of output method that takes the ratio of the gross domestic product (GDP) or gross value added (GVA) to the electrical consumption of commercial and industrial consumers in the region (Gorman, 2022; London Economics International LLC, 2013; Schröder and Kuckshinrichs, 2015; Shipley et al., 1972). As the reciprocal of energy intensity (Golušin et al., 2013), it is assumed that GDP will be reduced in direct proportion to the kWh interruption. The drawbacks are that it does not consider the portion of GDP that is not affected by power outages, nor does it factor in advanced warning periods or system restarts, and it cannot be applied to the residential sector because private households do not affect GDP except through their PCE (Schröder and Kuckshinrichs, 2015; Chioma, 2019).

$$MPF = \frac{Annual \quad GDP}{Annual \quad electric \quad consumption} \tag{1}$$

2.3.5. Household production method

The household production method requires forgoing work time to perform household chores that have market value, or leisure and sleep time. This method assumes that households are the centers of production and use electricity as an input to produce household services. The difference is that the electricity service interruption costs of a given household chore or service are equal to the market rate or cost of hiring a person to perform the chore or service (Gilmer and Mack, 1983). The outage cost is not that of the replacement but the difference in the costs to obtain the good in question (Caves et al., 1990; Gilmer and Mack, 1983).

2.3.6. Forgone leisure / wage rate method

The forgone leisure or wage rate method also assumes that households use electricity to produce goods and services, with leisure time equivalent to a customer's hourly wage rate (Gorman, 2022). Time is considered currency because all human activities require both time and goods, with these goods purchased through the money gained by working (Becker, 1965). An increase in income should equal a reduction in working hours and an increase in the number of non-working hours available to enjoy leisure activities. Thus, an additional hour of leisure equals an additional hour of work when the customer achieves an optimal ratio between work and leisure time.

2.3.7. Modifying a household production function by adding the cost of personal time

Considering that modern telecommunications can help overcome the difficulties of obtaining the market value or rate of many household activities and chores, the household production function should be further considered. Designed to measure the economic impact of daily household activities, this method avoids the subjective appraisal differences that vary from person to person, particularly because official data are now obtainable by regulating entity websites. Still, an element that requires regulation and is unique to residential sector household production functions is the investment of personal time to produce goods and services. Owning a good in and of itself can add value only when time is spent using it (Becker, 1965). From this perspective, time is treated as currency because households are only to be regarded as production units that generate added value, which is not to be confused with the more equitable perspective provided by "time banking" (Válek and Jašíková, 2013).

Any given subject may state that their time is worth more than anyone else's because it is the only time they truly own. While this cannot be argued from the subject's perspective, it is difficult to regulate and apply it evenly for all members within a society, as it would technically make all the activities in which people invest their time priceless and effectively violate the principles of supply and demand in our current economic structure. Although an economic structure can be exploited for inequity and injustice, particularly because it accepts debt and speculation as measures or adjustments to trade (Magdoff, 2023), providing an argument in favor of another economic framework is beyond the scope of this study.

Instead, we hope to better identify inequity and injustice within electric service decision-making by valuating time through existing societal economic constraints. Valuing household activities and income according to localized supply and demand while applying the market rate for the completion of a given chore or employment within a specific period can facilitate regulation toward energy justice. The household production method proposed by Gilmer and Mack in 1983 (Gilmer and Mack, 1983) appeared to be the most straightforward procedure, but as Caves, Herriges, and Windle noted in 1990 (Caves et al., 1990), this method was not feasible because it required data that were previously difficult to obtain. Despite overcoming the information barrier, Gilmer and Mack's method still requires attention, as it disregards chores that are undertaken on certain days within a week, such as work, commuting, homework, and laundry. Nor does the method convincingly address problems present in forgone-leisure methods, such as activities that are transferrable to another point in time, placed outside the household, or produced without electric power (Sanghvi, 1982; Caves et al., 1990; Shivakumara et al., 2017).

To address chores performed within a specific day of the week, as opposed to every day, the economic impact of a typical week should be evaluated instead of daily observance (De Nooij et al., 2007). This adaptation still suffers as a wage rate method, in that it falls short of addressing how certain activities are not time-independent and could be simply postponed to another moment during the day or week. In addition, a utility company could simply argue that it should not be forced to compensate a customer for the possibility of an outage occurring simultaneously with a specific activity, especially if the activity does not require electric power to be completed or could be substituted by another activity that cannot be evenly quantified through the market, such as leisure or sleep, which do not necessarily contribute to income directly but have a negative impact on productivity when reduced beyond a certain threshold (Becker, 1965; Slimani et al., 2018; Fucci et al., 2020).

Finally, the costs incurred by non-wage-earning household members should not be ignored. Although past studies have tried to determine the value of a housewife's time (Gronau, 1973) without considering tangible gender wage disparities, housewives or househusbands may not be the only non-wage-earning members in a household (these may include children and other unemployed adults) who can perform chores that have value, with the exception of sick and disabled household members under care.

We must not lose sight of the fact that the time invested in one activity may mean that another activity may have to be postponed. This condition is present when having to dedicate time and perhaps even travel to replace a good or service that is lost when the electric power supply is absent, instead of investing time in productive or preferable activities (Becker, 1965). A Sandia National Laboratory (SNL) resilience study addressed the timed-distance issue and titled the function as a burden, or the effort that a citizen must incur to acquire an infrastructure service divided by the individual's overall ability, which is directly proportional to the median household income of the evaluated sector (Sandia National Laboratories, 2018). The drawback of the SNL approach is the lack of context-quantifying effort (Wachtel et al., 2022). Moreover, it is not meant to address the inconvenience of dedicating time to replacing goods or services lost due to power outages, nor is it designed to value the forgone time that could have been invested in an activity that produces another service or good.

3. Methodology

In this section we propose two methods of quantifying outage costs, which we refer to as CESICs. The first method is a modified household production function, and the second is a macroeconomic production function adapted for application in the residential sector.

3.1. Proposed household production method

First, we estimate the CESIC as the total sum of the outage-related costs incurred during an interval of time. The proposed method considers both the direct and indirect costs associated with the loss of electric services as a function of the amount of time or duration of a given power outage, whose high-level expression is shown in Eq. (2).

In our method, direct costs are defined as all services and goods that would potentially be interrupted or lost during a power outage and must now be replaced at prices that must correspond to the evaluated region. We do not wish to presume which activities force customers to incur replacement expenses that they would have otherwise avoided should an outage not occur; these activities may differ from country to country, region to region, or customer to customer, for the reasons explained above. Instead, we aim to provide a framework that facilitates regulation in any given region. Hence, we propose the replacement of the direct costs related to goods and services deemed critical to human development in any given region, such as communication, refrigeration (for perishable food and medicine), nourishment (including cooking, groceries, and water intake), sanitation, hygiene, and education.

Indirect costs include the time and mileage costs that could potentially be incurred in the replacement or foregoing of a desired service that would ordinarily be acquired through electricity. Another indirect cost is the subjective value that individuals assign to a certain service, which is proportional to the length of the power outage. Through the proposed CESIC, both the VoLL and true costs of the electric service can be estimated using the high-level formulations in Eqs. (3) and (4). When analyzing Eq. (4) in detail, the annual costs paid to the utility usually correspond to those that the utility charges customers for delivered power, which should include the costs that the utility must incur for the deliverable plus profit. However, annual outage costs are those that customers must pay out-of-pocket to acquire certain goods and commodities when the utility fails to provide electric power. While the former expense is transferred by the utility to customers, the latter is imposed upon the customer when the utility fails to honor its contractual agreement.

$$CESIC = Direct \quad Costs + Mileage \quad Costs + Time \quad Costs + Subjective \quad Value \tag{2}$$

$$CESIC_{VoLL} = \frac{CESIC(During \quad Outage \quad Period)}{Estimated \quad Lost \quad or \quad Unserved \quad Consumption \quad During \quad Outage \quad Period(kWh)} \tag{3}$$

$$True \quad Cost \quad of \quad Electric \quad Service = \frac{Annual \quad Costs \quad of \quad Energy + Annual \quad Costs \quad of \quad Not \quad Having \quad Energy}{Average \quad Annual \quad Consumption \quad (kWh)} \tag{4}$$

A utility may rightfully question whether it should be held accountable for a power outage that may or may not affect a service or activity during a given part of the day. Still, we must state that the longer the duration of the outage, the more probable the risk that the electrically supplied service would be interrupted. Because we assume that replacing each of the services and goods are mutually exclusive events, that is, they do not overlap, the solution is to explore the sum probability of interceptions from all possible household service or good replacement events and the power outage event occurring simultaneously. Because the sum of all daily household service or good replacement times should be 24 h, the sum of the interceptions should be equal to the probability of the outage event, which is illustrated in Eq. (5) and applied to Eqs. (7), (8), and (10). Although Eq. (5) can be used to build a more general approach outside the 24-h window, this is beyond the scope of this study.

$$\sum\nolimits_{(i=1)}^{m} P(i \cap j) = \sum\nolimits_{(=1)}^{m} P(i) \cap P(j) = P(j) \tag{5}$$

where $P(i) = \frac{U_{DR_i}}{24} P(\quad j) = \frac{j}{24} with \begin{cases} j = 24, j > 24hrs\& \\ 0 < j \le 24, otherwise \end{cases}$ i=Service to be replaced or forgone$j$=Number of hours of outage or outage time, from 0 to 24. Above 24 h, the value of j = 24.U_{DR_i}=Daily hours of use of forgone good or service i to be replaced$P(i)$=Probability direct service or good i's daily hour of use event in U_{DR_i} hours occurring within a period of 24 h.$P(j)$=Probability outage event of j hours occurring within a period of 24 h.

The proposed method is subject to limitations: It presently offers low-bound outage cost estimates because it saturates upon reaching the first 24 h of the power outage time and does not quantify subjective valuations, assuming them to be equal to zero. Further research is required to better ascertain these subjective valuations and better estimate the costs related to fatigue and mental health complications, among other consequences, arising from long periods of electrical service interruption. Furthermore, it represents a low-bound worst-case scenario, in which customers have not employed preparatory or mitigation methods.

Subjective valuations require a framework developed through a holistic, in-depth discussion that includes the nature and level of human satisfaction, frustration, and valuation of life. Apart from any valuation that an electricity-supplied service can have for any given subject, the level of satisfaction that the service can provide will be affected by any level of frustration related to both the moment in time at which the service is lost and the inconvenience of having to assign personal or household time to replace the lost service. The impact of collateral costs resulting from the absence of electric power, such as environmental or societal costs (fuel spills, riots, etc.), can also prove difficult to predict and document, let alone subjectively quantify. Time constraints offer broad range of valuations and situations onerous to standardize and lie beyond the scope of this study. Although they are presently assumed to be zero, their existence is recognized as part of the final valuation of CESIC estimates.

3.1.1. Hourly CESIC Estimation

We begin by quantifying the hourly CESIC ($CESIC_H$) as the total cost of each energy service replacement as a function of outage hours and expand the high-level expression, as shown in Eq. (2).

$$CESIC_H(\quad j) = \sum\nolimits_{1 \le i \le m} M_{Hh} \quad C_{T_i}(\quad j) \tag{6}$$

with

$$C_{T_i}(\quad j) = \left[\quad C_{D_i}(j) + C_{d_{DR_i}}(j) + C_{T_i}(\quad j) + V_{S_i}(\quad j) \right]$$

where

$C_{T_i}(j)$=Total costs of a replaced or forgone energy service corresponding to service i as a function of j

M_{Hh}=Number of household members, subject to occupation

i=Service to be replaced or forgone

j=Number of hours of outage or outage time, from 0 to 24. Above 24 h, the value of j = 24.

$C_{D_i}(j)$=Direct cost of lost service or good i to be replaced or forgone as a function of j

$C_{d_{DR_i}}(j)$=Distance cost to replace an energy service corresponding to service i as a function of j

$C_{T_i}(j)$=Time cost to replace energy service corresponding to service i as a function of j

$V_{S_i}(j)$=Subjective value corresponding to service i as a function of j

It is important to note that some services will become unavailable and/or need to be replaced after a specific period of time, such as perishable groceries spoiling after an outage of 4 h or more due to lack of refrigeration (Center for Disease Control and Prevention, 2023), or utility water pressure failure after a 24-h outage because we presume that the outage will stop supplying the electric pumps of the water utility distribution system. Meal replacement, owing to the lack of electrically facilitated cooking, is not considered when the outage time is less than or equal to an hour, although the number of meals to be replaced per day depends on the outage time.

3.1.2. Direct costs

The direct costs incurred in the replacement or discontinuation of a service are calculated by the purchase of goods to provide a service that was previously provided for or powered by the utility, including monthly subscriptions and payments for services. The costs must be expressed in hourly increments. Again, it must be stated that the prices of goods and services to be replaced must correspond to the evaluated region. To standardize the quantification of direct costs, we obtain either the product of the purchase costs divided by the hourly period between purchases or the product of the subscription costs multiplied by the number of outage hours divided by the hourly period between payments, as shown in Eq. (7).

For example, to replace electric refrigeration, customers would have to purchase ice bags to provide the relatively cold temperature necessary to keep perishable foods and medicines from spoiling. The purchase amount is then divided by the number of hours required to make another purchase. The direct replacement cost for refrigeration would be that of the ice bags, whereas the direct replacement cost for nourishment would originate from the purchase of a meal because it would not be possible to cook at home and even perishable groceries when spoiled after 4 h due to a lack of refrigeration. A forgone service example would be a telecommunications service that will not refund clients for the service time lost during a potential outage period that deenergizes communications towers.

$$C_{D_i}(j) = \left[\frac{(C_{PG_i} + C_{SG_i})}{T_{P_i}} - C_{AUC_i} \right] \times P(j) \tag{7}$$

whereC_{PG_i}=Purchase cost of good or service to be replaced or forgone corresponding to service $i$$C_{SG_i}$=Subscription cost of good or service to be replaced or forgone corresponding to service $i$$i$=Service to be replaced or forgone$j$=Number of hours of outage or outage time, from 0 to 24. Above 24 h, the value of $j = 24$.T_{P_i}=Daily, monthly, or yearly period in hours between purchase or payment of service to be replaced or subscription forgone corresponding to service $i$$C_{AUCi}$=Hourly avoided utility electric consumption cost of service due to electrical supply interruption$P(j)$=Probability outage event of j hours occurring in a period of 24 h.

3.1.3. Mileage costs

The cost of replacing energy services requires the use of motor vehicles. This is calculated using standard milage rates applicable to the affected region and does not include vehicle-mileage depreciation or reduction. Walking and other travel methods that do not involve motor vehicles are included in Eq. (10).

$$C_{d_{DR_i}}(j) = No.of \quad miles \times C_{Milleage} \times P(j) \tag{8}$$

3.1.4. Time Costs

Time costs have two components: service replacement time, and the weighted market value of time.

$$C_{T_i} = t_{DR_i}(j) \times T_{WMC_O} \tag{9}$$

3.1.5. Service replacement time

The time taken to replace an energy service is calculated as the sum of the to-and-from distance necessary to directly replace a service over the traveling velocity plus the time taken to purchase a direct replacement of a service, as shown in the following equation:

$$t_{DR_i}(j) = \left(\frac{2d_{DR_i}}{v} + t_{DR_i} \right) \times P(j) \tag{10}$$

wheret_{TR_i}=Total time to replace service corresponding to service $i$$d_{DR_i}$=Distance to travel to replace service corresponding to service $i$$v$=Traveling speed to replace service$i$=Service to be replaced or forgone$j$=Number of hours of outage or outage time, from 0 to 24. Above 24 h, the value of $j = 24$.t_{DR_i}=Time taken to directly purchase the service corresponding to service i in store or other commercial facility.$P(j)$= Probability outage event of j hours occurring in a period of 24 h.

3.1.6. Weighted market cost of a customer's time

To calculate the weighted market cost of a customer's time, Gilmer and Mack's market cost method is adapted and applied to De Nooij, Koopmans, and Bijvoet's weekly time valuation, as suggested in *Section 2.3.4* . The weighted market cost of time is related to household time, which should not be confused with time within a house. Members of a household must undertake certain key activities to ensure that they develop in our market-based society. If members cannot perform their activities, a replacement must be acquired. The replacement value given to households and personal activities or chores will be that of hiring a person to execute them at a market value cost, along with income, if the customer is employed. The wage paid for each service to be replaced shall be in accordance with the U.S. Bureau of Labor Statistics (Division of Occupational, 2022) when applied to any of the 50 U.S. states or territories. As such, the method can be applied to any of the 50 U.S. states and territories or any other country that has wage data readily available through the Internet. All activities that do not involve household chores, sleep, work, childcare, and commuting should be considered leisure activities. Again, we do not presume to define the household activities that should be weighed and instead wish to provide a framework to derive the average market cost of a person's weekly time in relation to their average weekly activities.

$$T_{WMC_O} = \frac{\sum_{1 \le k \le m} (Q_k \quad W_k)}{168 Hours} \tag{11}$$

whereT_{WMC_O}=Weighted market cost of a customer's time per occupation.k=Number of disaggregated lifestyle activityQ_k=Hours per week devoted to lifestyle activity $k$$W_k$=Hourly rate in market for occupation corresponding to activity k

Special considerations have been made for sleep or leisure because they are not quantified by a monetary value, not because they have no value, but because we find making them arbitrarily equivalent to a person's wage rate. Instead, other studies state that their reduction will decrease a person's overall productivity; hence, the rate of other household and personal activities will decrease proportionally. For some customers, an outage during sleep may interrupt their sleep patterns, particularly if they live in areas with high heat or cold. The percentage of actual customers whose sleep is interrupted is beyond the focus of this study; instead, we provide a framework to factor the loss of productivity for regulatory purposes.

The probability of both the predefined sleep time and the power outage event should be considered, subject to the length of the power outage, where the reduced sleep time must correspond to a reduction in the value for all other activities. Accounting for this effectively alters Eq. (11) by substituting the input parameter W_k into Eq. (12). Unitary efficiency is presumed to correspond with adequate sleep time, which is arbitrarily established at 8 h. The reduction in sleep time should reduce the value of all quantified activities up to an arbitrary minimum of 4 h of sleep, to which the maximum reduction or minimum efficiency is achieved. Lacking a consensually accepted method within the scientific community, any value between unitary and minimum efficiency is interpolated, as in *Equation (13)* for the time being. Ultimately, the value of the remaining activities is reduced by the minute of the power outage until an outage time of 16 h and 59 min is reached, where sleep time will be reduced to the 4-h limit (See Fig. 1). Unlike sleep time, the loss of efficiency due to a lack of leisure time is not prorated. In other words, leisure-dependent efficiency will either be unitary when enjoying at least the minimum daily leisure time or fully reduced.

$$W_{k_{Adj}} = W_{kS} - W_{kL} \tag{12}$$

$$W_{kS} = \begin{cases} \eta_{Q_1} \quad W_k, & Q_1 < Q_{1_{Max}} \& \\ W_k & , otherwise \end{cases}$$

$$W_{kL} = \begin{cases} \eta_L \quad W_k, & Q_2 < Q_{2_{Min}} \&\& \\ 0, otherwise \end{cases}$$

whereW_{kS}=Hourly rate in market for occupation corresponding to activity k adjusted for lack of sleepW_{kL}=Hourly rate in market for occupation corresponding to activity k adjusted for lack of leisure$\eta_{Q_1} = \eta_S + \frac{1-\eta_S}{(Q_{1_{Max}} - Q_{1\,Min})}(Q_1 - Q_{1\,Min})(13)\eta_S$=Reduced efficiency due to lack of sleep.η_L=Reduced efficiency due to lack of leisure time.$Q_{1\,Max}$=Arbitrary maximum limit of 8 h of sleep per day.$Q_{1\,Min}$=Arbitrary minimum limit of 4 h of sleep per day.Q_{2Min}=Arbitrary minimum limit of 15 min of leisure per day.

Applying the efficiency changes to the market value of the household chores or activities, Eq. (11) is effectively replaced by Eq. (14). The probability of a decrease in sleep time due to a power outage will result in the sleep time being less than the established limit, adding the adjusted loss of value to the market rate of the activity $\left[W_{k_{Adj}} (1 + \eta_{Adj}) \right]$.

$$T_{wmv_o} = \begin{cases} \dfrac{\sum_{1 \le k \le m} [Q_k \quad W_{k_{Adj}}(1+\eta_{Adj}) \quad]}{168Hours}, & Q_{1_{Adj}} < 8 \\ \dfrac{\sum_{1 \le k \le m}(Q_k \quad W_k)}{168Hours} & otherwise \end{cases} \quad (14)$$

where $\eta_{Adj} = 1 - \frac{Q_{1_{Adj}}}{Q_1} Q_{1_{Adj}} = \begin{cases} Q_1 \quad -j \times P_{1j}, Q_1 - j \times P_{1j} > 4hrs\&\& \\ 4, otherwise \end{cases} P_{1j} = P(Q_1 \cap j) = P(Q_1) \times P(j) = \frac{t_{Q_1}}{24} \times \frac{j}{24}$

3.1.7. VoLL and Annual CESIC Estimation

Once the $CESIC_H$ is estimated, the total CESIC per electric power outage can be calculated. The $CESIC_{Outage}$ is the product of the hourly CESIC estimation adjusted by the outage probability and actual outage time of the event registered during the year (Eq. (15)). Both the VoLL and annual CESIC ($CESIC_A$) can be calculated using available consumption data or averaged for a period. When the lost consumption is unknown, the product of the outage hours times the average hourly consumption can be employed, as shown in Eq. (16). The annual CESIC can be obtained using three methods, as shown in Eq. (17). The first two use reliability metrics if provided by the local electric utility and no year-long measured power-outage data are available. The problem with the first method is that it does not properly represent the reality of many customers, as it presumes that the total number of SAIDI hours is composed of a specific number of interruptions of CAIDI hour length. In many case studies, most electric power interruptions occurred for lengths equal to or less than an hour during the year. Hence, we propose a second method that involves the $CESIC_{EDF}(j)$, which is a modified exponential distribution function of the SAIFI that distributes the frequency of outages per outage length in half-hour intervals, times outage times (j) and hourly $CESIC_H(j)$. The third method is the sum of all $CESIC_{Outage}$ estimations obtained from actual measured power outages during the year, which is more precise because it captures the harsh reality of many communities, whereas the former two deal with averages that may or may not apply to outliers.

$$CESIC_{Outage} \quad (\quad j) = t_j \times \begin{cases} CESIC_H(24), j > 24 \\ CESIC_H(\quad j), 0 < j \le 24 \end{cases} = j \times n_j \times \begin{cases} CESIC_H(24), j > 24 \\ CESIC_H(\quad j), 0 < j \le 24 \end{cases} \quad (15)$$

where j = Number of hours of outage or outage time $t_j = j \times n_j$, or total outage time of outage type of j hours. n_j = Total number of interruptions per outage type of j hours.

$$VOLL_{CESIC}(\quad j \quad) = \frac{CESIC_{Outage} \quad (\quad j)}{P_{Lost \quad Consumption}(\quad j)} \approx \frac{CESIC_{Outage} \quad (\quad j)}{j \times \frac{P_{Annual}}{8760}} \quad (16)$$

where

$$CESIC_{EDF}(\quad j) = j \times \left\{ \left[\quad j \quad \times \left(1 - e^{-\frac{1}{CAIDI_{Hours}}}\right) \right] - \sum_{i=0}^{\frac{j-\Delta j}{\Delta j}} \left[i \times \Delta j \times \left(1 - e^{-\frac{1}{CAIDI_{Hours}}}\right) \right] \right\} \times SAIFI \times CESIC_H(\quad j) \quad (17)$$

3.1.8. True cost of utility, auxiliary generator or renewable energy system electricity

Annual CESICs are ultimately considered in determining the true costs of electric supplied energy from Eq. (4) by including the annual electric service interruptions as part of the price that must be paid to have an electric service regardless of the source, as displayed in Table 3. This means that one can estimate the true costs of utility-serviced electricity for a given region, whose reliability metrics or measurements are available, as shown in Eq. (18), which can be adjusted for other sources of electricity generation: the emergency generator supplies electricity, as represented in Eq. (19), which is obtained by estimating the unaccounted costs of a person purchasing fuel, where the person's time and mileage spent in obtaining fuel are multiplied by the frequency during which fuel would have to be purchased per year (f_A). We can also estimate the effect of electric utility unreliability when optimizing energy costs through RES sizing for hybrid (utility/RES) energy sources, as shown in Eq. (21). In this equation, the percentage of time that the RES does not supply is translated as a complement to the loss of load probability (LOLP) of the RES. This method was fully elaborated on in our previous research (Garcia Cooper, 2023) and will be expanded upon in a later publication. If reliability and resilience are improperly addressed by regulators, the true costs of utility-serviced electricity and other sources can be determined state-wide, district--wide, or per community, depending on the granularity and availability of the reliability metrics or measurements. This gives households and communities the opportunity to make proper "apples-to-apples" comparisons when deciding to invest in alternate energy sources (García Cooper and Castro Sitiriche, 2022).

$$True \quad Cost_{Utility} \quad = \frac{Average \quad Annual \quad Utility \quad Costs + CESIC_A}{Average \quad Annual \quad Consumption(kWh)} \quad (18)$$

$$True \quad Cost_{Emergency \quad Generators} = \frac{Average \quad Annual \quad Fuel \quad Costs + O\&M + C_{FPA}(j)}{Average \quad Annual \quad Consumption(kWh)} \quad (19)$$

$$C_{FPA}(j) = \left[\quad C_{d_{DR_i}}(j) + t_{TR_i} \quad (\quad j) \times T_{WMC_O} \right] \times f_A \quad (20)$$

$$CESIC_A = \begin{cases} CESIC_H(\quad CAIDI_{Hours}) \times SAIDI_{Hours} & Only \quad when \quad reliability \quad metrics \quad are \quad available \\ \sum_{0.5 \le j \le 24} [CESIC_{EDF}(j)] & Only \quad reliability \quad metrics \quad are \quad available, j+ = 0.5 \\ \sum_{0 < j \le N} [\quad CESIC_{Outage} \quad (\quad j)] & Measured \quad outage \quad data \quad is \quad available(preferred) \end{cases}$$

$$True \quad Cost_{RES} = \frac{Annuity_{RES} + Average \quad Annual \quad Utility \quad Costs + CESIC_A \times (1 - LOLP_{RES})}{Average \quad Annual \quad Consumption(kWh)} \tag{21}$$

3.2. Proposed macroeconomic production method

Although our proposed household production function method of the CESIC calculation yields a fair estimate of the minimum impact that an unreliable electric power grid can have on an individual or household's finances, it does not assess the impact of electric service interruptions in the residential sector on the overall economy. Therefore, we propose a macroeconomic CESIC valuation method that approximates the impact of electricity service interruptions in the residential sector.

First, to adapt a macroeconomic method that can represent the residential or household sector, we observe the PCE instead of focusing on GDP. The PCE is the part of GDP that is also known as "consumer spending," which measures the goods and services purchased by "persons," households, and nonprofit institutions that serve households (U.S. Bureau of Economic Analysis, 2021). We require a simple estimation of how much electricity-dependent and/or electricity-supplying industries contribute to GDP. For this, we note the estimated percentage of the electric power industry's contribution to a country's GDP (Bradley, 2017; Center for Sustainable Systems, 2022) while assuming that water-dependent industries (Spit et al., 2018), telecommunications (Thompson and Analytics, 2020; Kathuria et al., 2009), and refrigeration industries (International Institute of Refrigeration IIR, 2015) depend on the electric power industry to be able to contribute to the GDP and/or GVA. These percentages are applied to the PCE to obtain an annual estimate and divided by the total annual consumption, as shown in Eq. (22).

$$CESIC_{MPM} = \frac{PCE \quad (\epsilon + \omega + \tau + \sigma)}{Annual \quad consumption \quad kWh} \tag{22}$$

wherePCE=Personal consumption expendituresϵ=Percentage of contribution to the total GDP or GVA of the electric power industry.ω=Percentage of contribution to the total GDP or GVA of water dependent industries.τ=Percentage of contribution to the total GDP or GVA of telecommunications industry.σ=Percentage of contribution to the total GDP or GVA of refrigeration industry.

4. Results

4.1. Proposed household production method

When presenting the results of our proposed household production method, we begin with a sample of costs per good or service that needs to be replaced or forgone, as shown in Table 4. The services considered are communications (including household data plan, mobile phone, and Internet channel subscriptions), refrigeration, tertiary education, cooking, laundry, meal replacement, grocery replacement after 4 h and 24 h, water, housekeeping requiring water, and dishwashing. Once the $CESIC_H$ is calculated for a given outage time, the total $CESIC_{Outage}$ is calculated. Although these are not necessarily all goods and services that are compromised when affected by an electric power outage, they are tied to or related to goods and services deemed critical.

In, Fig. 4 the level of change from the different costs that comprise the CESIC as the outage time increases can be appreciated. At an initial glance, time costs appear to be one of the most important characteristics of hourly CESIC estimation, as they bear the most weight as the outage time increases. This makes sense when the number of goods and services that need to be replaced increases with longer outage times. Time costs are distinctively different between formally and non-formally employed individuals. The answer can be obtained by observing Table 5, which shows that the amount of time spent on activities with a monetary market-based value plays a significant role in the overall market-based value of a person's time. A formally employed person would spend 40 h a week undertaking an activity that yields a salary, whereas a

Table 3
True Costs of Electricity.

Electricity Service	Costs of Energy	Costs of Not Having Energy
Utility	Annual Utility Costs	Annual Outage Costs
Emergency Generator	Annual Fuel Costs + Annual Operation and Maintenance Costs + Total Mileage and Time Costs purchasing fuel	Annual Outage Costs × % of Time Emergency Generator does not supply
RES	Investment Annuity + Annual Operation and Maintenance Costs + Annual Costs of Auxiliary Supply	Annual Outage Costs × % of Time RES does not supply

Table 4
Sample Disaggregated CESIC Costs for a Citizen Not Formally Employed During a 24-h Outage.

Service or Good to be Forgone or Replaced	Direct Costs $/h	Daily Use (hours)	Period between Purchase (hours)	Purchase Time	Distance (miles)	Distance (hours)	Mileage Cost	Total Time	Time Cost
Communications	$ 0.20	24	720	-	-	-	$ -	-	$ -
Refrigeration	$ 0.12	24	48	0.25	1	0.10	$ 0.32	0.35	$ 0.74
Education	$ -	-	3650	-	-	-	$ -	-	$ -
Cooking	$ 0.35	2	24	-	-	-	$ -	-	$ -
Laundry	$ 0.37	0.43	24	-	-	-	$ -	-	$ -
Meal Replacement	$ 0.63	2	24	0.50	7.7	0.77	$ 2.46	1.27	$ 2.69
Perishable Groceries Replacement	$ 0.70	24	360	2.00	1	0.05	$ 0.16	2.05	$ 4.34
Water	$ 0.21	24	24	0.25	1	0.10	$ 0.32	0.35	$ 0.74
Housekeeping requiring Water	$ 0.17	0.5	24	-	-	-	$ -	-	$ -
Dishwashing	$ 0.15	0.417	24	-	-	-	$ -	-	$ -

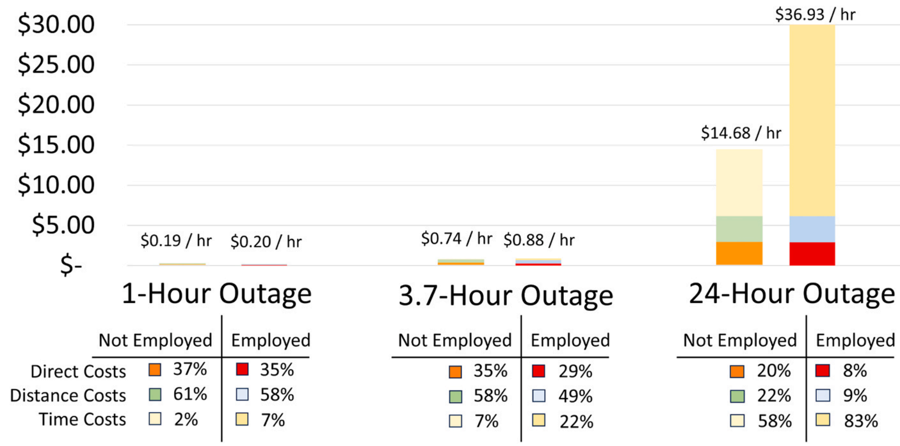

Fig. 4. Percentage of distribution of disaggregate costs within the total CESIC per outage time, for citizens not formally employed vs employed citizens working at the Puerto Rican mean of $14.65 / hr., where distributions or percentages change as outage time increases.

Table 5
Weighted Market Cost of Time for a Customer Not Formally Employed.

Activity	Weekly Hours	$ / Hour	$ / Week
Sleep	56.00	$ -	$ -
Leisure	88.58	$ -	$ -
Cooking	14.00	$ 11.16	$ 156.24
Dishwashing	2.92	$ 8.65	$ 25.23
Housekeeping	3.50	$ 8.35	$ 29.23
Laundry	3.00	$ 8.82	$ 26.46
Employed Labor	0.00	$ -	$ -
Childcare	0.00	$ -	$ -
Commute	0.00	$ -	$ -
Tertiary Studies	0.00	$ -	$ -
Totals	168		$ 237.15

Weekly/Hourly Weighting of Time $ 1.41.

person not formally employed would otherwise dedicate this time to leisure.

The weighted market cost of a non-formally employed customer's time, represented in Table 5, is treated as a benchmark when income is not considered a part of a household's weekly activities. Not having formal employment does not mean that a person's time has no value, and wasting that person's time should equate to costs. We must point out that the weighted market cost of time is not subject to power outages because it represents the price of a person's time according to the average weekly activities that they invest their time in, which they must now place aside to replace a forgone service or good; this will depend on there being an outage, and finally on the time that must be invested in finding a replacement for the given service or good.

These are not all the activities that are undertaken by every single household during a typical week; we must again state that we are providing a framework and identifying key household activities that we deem relevant for human development within our culture, so that it may facilitate the decision-making processes of regulators and policymakers. However, these may differ in other regions.

Household and personal lifestyle functions evaluated include sleep, leisure, tertiary education, work, commuting to work and/or school, domestic cooking, dishwashing, housekeeping, laundry, and childcare. Any activity other than those mentioned are treated as leisure. Time spent on household activities during a typical week and weekdays is chosen arbitrarily, with a fixed sleep duration of 8 h, commute time derived from the traveling distance and velocity from home to work, and leisure time being any remaining time within the 24- or 168-h periods. Median occupational hourly wages for domestic cooking, dishwashing, housekeeping, laundry, and childcare are obtained from the U.S. Bureau of Labor Statistics (Division of Occupational, 2022). The commuting cost is the product of the traveling distance from home to work and/or school times the local commercial mileage rate (U.S. Internal Revenue Service IRS, 2021), as described in Eq. (10). Tertiary studies include the present value of having lost a semester due to power outages, that is, the hourly price of a semester plus the present value of the expected hourly wage difference of the chosen career field's current median wage (Division of Occupational, 2022) versus the expected hourly wage upon graduation,

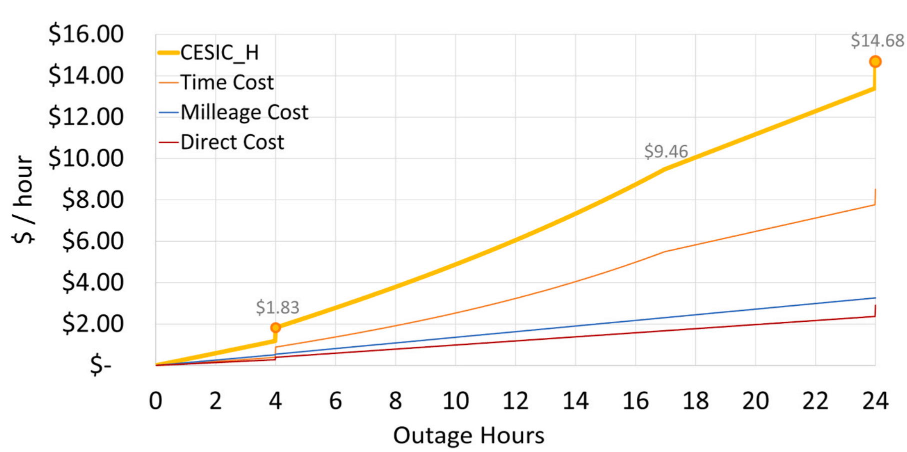

Fig. 5. Cost per outage time of 1 min to 24 h, adjusted for sleep interruption. Note that the time costs increase linearly after 16 h and 59 min when sleep time can no longer be reduced or interrupted by power outages.

Table 6
Weighted market value of time, $CESIC_{H,}$ and CESIC for each outage per customer occupation.

Customer Occupation	Weighted Market Cost of Time [$ / hr.]	$CESIC_H$ [$ / hr.]			$CESIC_{Per\ Outage}$ [$ / Outage]		
		Outage Hours			Outage Hours		
		1	3.7	24	1	3.7	24
Not formally employed	$ 1.41	$ 0.19	$ 0.74	$ 11.84	$ 0.19	$ 2.74	$ 284.21
Working 20 h at $7.25 /h	$ 2.64	$ 0.19	$ 0.79	$ 16.79	$ 0.19	$ 2.92	$ 402.86
Working 40 h at $7.25 /h	$ 3.50	$ 0.20	$ 0.82	$ 20.26	$ 0.20	$ 3.04	$ 486.13
Working 40 h at Puerto Rico's Mean wage of $14.65 /h	$ 5.10	$ 0.20	$ 0.88	$ 26.68	$ 0.20	$ 3.27	$ 640.29
Small Business Owner with gross earnings of $32.18 per hour	$ 9.43	$ 0.21	$ 1.05	$ 44.07	$ 0.21	$ 3.88	$ 1057.66
Public University Undergraduate Student	$ 2.00	$ 0.19	$ 0.76	$ 14.19	$ 0.19	$ 2.82	$ 340.62
Private University Undergraduate Student	$ 2.11	$ 0.19	$ 0.77	$ 14.66	$ 0.19	$ 2.84	$ 351.83
Graduate Student at Public University	$ 2.01	$ 0.19	$ 0.76	$ 14.25	$ 0.19	$ 2.83	$ 341.95
Public University Undergraduate Student working 20 h a week at $7.25 /h	$ 2.86	$ 0.19	$ 0.80	$ 17.66	$ 0.19	$ 2.95	$ 423.89
Private University Undergraduate Student working 20 h a week at $7.25 /h	$ 2.98	$ 0.19	$ 0.80	$ 18.13	$ 0.19	$ 2.96	$ 435.10
Public University Graduate Student working 20 h a week at $7.25 /h	$ 2.87	$ 0.19	$ 0.80	$ 17.72	$ 0.19	$ 2.95	$ 425.22

Table 7
Measured power outages and CESIC for a family in a western region of Puerto Rico.

Outage Type Frequency	Outage Length	Total Outage Time (Hours)	Outage Costs
17	0.083	1.42	$ 0.12
14	0.10	1.40	$ 0.14
10	0.12	1.17	$ 0.14
26	0.13	3.47	$ 0.46
30	0.15	4.50	$ 0.68
65	0.17	10.83	$ 1.81
37	0.50	18.50	$ 9.60
2	2.75	5.50	$ 15.43
1	3.75	3.75	$ 14.45
1	4.00	4.00	$ 32.51
1	8.75	8.75	$ 169.19
1	12.25	12.25	$ 365.65
1	14.50	14.5	$ 551.36
1	15.75	15.75	$ 679.47
207		106.47	$ 1841.01

factoring in an average 2% inflation depreciation for the years 2016–2021 (Bureau of Labor Statistics, 2023b).

Leisure is not calculated as a value per se, as we are not convinced that leisure should be valued as income, as the literature in Section 2.3.3.3 supports. Instead, our approach is to reduce the monetary price of all other lifestyle activities by 15% (Slimani et al., 2018), except for sleep, if it does not meet an arbitrary daily minimum of 15 min/day. For similar reasons, sleep is not calculated; instead, it would reduce the monetary price of all other lifestyle activities by 35% (Fucci et al., 2020) if the person does not sleep for an arbitrary daily minimum of four hours. If the economic literature points in a direction in which either leisure or sleep is assigned monetary value, the proposed model can be adjusted accordingly.

It is important to note the impact that a lack of leisure and sleep time can have on overall productivity and how it may relate to people's time per occupation, as both should diminish when performance is reduced. Therefore, a compensation method for potential sleep interruptions is included. The same does not apply to leisure as it could be replaced with another leisure activity that does not require electric services. Factoring the interpolated degradation of productivity efficiency due to a lack of sleep yields a nonlinear slope when graphing against time, which becomes linear when sleep can no longer be reduced or the minimum sleep time of 4 h is reached, as shown in Fig. 5. The final result is greater than that displayed in Fig. 4 because the reduction in value of other activities due to interrupted sleep is compensated.

The hourly and outage CESIC can be estimated as shown in Table 6, where we provide the results for different customer occupations, including students, after weighing them in education as part of their direct costs. It is important to remember that outage hours beyond the 24-h maximum are accounted for as 24 h of electric service interruption for the purpose of hourly CESIC calculations. The 3.7-h column corresponds to the local CAIDI resilience metric, which represents the average electric service interruption time per electric utility customer in Puerto Rico (Puerto Rico Energy Bureau, 2022).

When calculating the annual CESIC with available utility reliability metrics, we obtain the hourly CESIC using Puerto Rico's 3.7-h CAIDI reference as the outage time and then multiply it by the islands' average SAIDI of 27.44 h per customer. Consider a household comprising two adults earning Puerto Rico's mean wage of $14.65/ h. per 20 weekly hours and one infant child. For an hourly CESIC of $2.15 per adult and none for the child because the child is not at an age to perform household chores, the annual power-outage cost using the first method of annual CESIC calculation amounts to $117.77. If the three household members consume equal amounts of power, at an average of 0.375 per kWh, the household's VoLL would estimate $11.45/kWh. Instead of the advertised residential utility rate of $0.28/kWh, the true cost for staying connected to the electric power grid is equivalent to $0.32/kWh. Again, this first method falls short of reflecting the reality of the household, which lies in a remote outlying circuit. If we apply the second (exponential distribution function) method of the annual CESIC calculation, we obtain up to $523.16 in annual outage costs, a household VoLL of $50.84/kWh, and a true cost of $0.44/kWh.

Table 7 lists the actual measured power outages and CESIC values per outage type for the household described above. The annual CESIC for the two adults increases to $1841.01, the VoLL is $46.11/kWh because of the greater outage time, and the true cost of utility-serviced power is $0.84/kWh. Estimating the annual CESIC with actual measured power outages presents a different scenario compared to using reliability metrics.

4.2. Proposed macroeconomic production method

To calculate the economic impact that Hurricane Fiona had on Puerto Rico's economy, as opposed to the potential household impact, with a GDP of $111.702 billion and a PCE of $54.225 billion (U.S. Bureau of Economic Analysis, 2021), the direct contribution of the electricity industry was estimated at 4.8% (Center for Sustainable Systems, 2022), 1.6% of telecommunications (Thompson and Analytics, 2020), 26% of water-dependent sectors (Spit et al., 2018), and 1.7% of the refrigeration industry (International Institute of Refrigeration IIR, 2015). The latter three depend on electricity to operate, and the adjusted PCE would approximately be $18.49 billion. With a yearlong consumption of 16,122,909,046 kWh, we arrive at a $CESIC_{MPM}$ of $1.15 / kWh. Having estimated a loss of electricity consumption of 249 GWh during Hurricane Fiona in September and October 2022 and a loss of 57 GWh during the island-wide Costa Sur power plant fault blackout in April 2022, we estimated $286,135,748 and $65,156,884 in losses, respectively.

5. Discussion

Early in the literature review, we established the need to estimate outage costs correctly and use these estimates to highlight the hardships that many households frequently experience because of regular and long power outages from an unreliable and unresilient power grid. In Puerto Rico, reliability metrics alone have not conveyed a sufficient message to regulators and policymakers, as utility personnel and warehouse inventories shrunk to pay off debt, giving rise to higher outage times per interruption. Meanwhile, maintenance and grid-hardening investments remained sluggish at the customer's expense. Proper annual CESIC quantification can allow for VoLL and the true costs of electric service estimates and serve as indicators for regulation and policymaking that steer us toward equity and energy justice. Should utilities and/or regulators ignore VoLL estimates and choose not to reimburse citizens for their lost load, the true costs of utility electric services would allow potential prosumers to evaluate the overall cost of remaining with the electric utility versus the total cost of owning or financing an RES.

While it may be argued that the true cost would suggest that the utility should raise the rate by incrementing the annual utility cost component to reduce the annual outage cost component that it imposes upon customers, we must first understand each component. First, the referenced outage costs are the customer's outage costs and not those of the utility. As previously mentioned, these are the out-of-pocket costs that customers must incur when the utility does not deliver power according to the contract. The referenced outage costs are not those incurred by the utility when an outage occurs, which are factored into the utility rate. Second, the annual utility cost component does not necessarily have to be increased; it can be lowered by implementing higher efficiency measures and/or by allocating more funding to O&M, personnel, and inventory. The latter can be achieved by raising the utility rate or redistributing existing utility funds.

It is apparent that PREPA sacrificed resilience and reliability by reducing O&M expenses, personnel, and inventory to be able to comply with its contractual obligations, of which principal and interest bond payments made up 95% of these obligations on average. For PREPA to lower grid unreliability, they need to reinvest in O&M, personnel, and inventory, either by raising the utility rate or renegotiating the power revenue bond agreements. Both options are off the table as they have heavy political implications, making them beyond the scope and purview of this study. Increasing an already high utility rate would have devastating economic and social implications for a population already laden with draconian austerity measures. Renegotiating power revenue bond agreements would have profound U.S. interstate economic and political implications, as described by a former House Representative within a House Committee on Natural Resources Congressional hearing held in 2016 (House Committee on Natural Resources GOP, 2024).

While the availability of reliability metrics has allowed us to estimate the minimum low-bound outage costs for each of the islands' 902 neighborhoods and communities whose median income and reliability metrics are available (see Table 9 in the Appendix) (Moscoso-Cabrera et al., 2023), such a method typically yields less than quantifying the total interruption time in the outage length categories, as shown in Table 7. For example, if we were to strictly observe the 31.6 SAIDI hours and the SAIFI of 11.24 in the LUMA/NREL study in Vieques and Culebra (Nassif et al., 2022), the CAIDI can be calculated to be 2.811 h. After considering a median income of $7383 for Vieques and $25,500 for Culebra, a minimum yearly estimate of $542,628 can be obtained in residential losses not directly tied to the overall economy (for 5499 residential customers or 4378 in Vieques and 1121 in Culebra). This equates to an annual $98.68 in annual losses for households with a statewide average of 2.8 residents, and at an average monthly consumption of 400 kWh purchased at $0.28/kWh, the true costs of being connected to the grid would be $0.30/kWh. This approach does not represent the reality of many households on both islands; however, if granular data are not available, it should be considered as a minimum bound estimate.

When applying the adapted exponential distribution of the SAIFI at half-hour intervals up to 24 h, using the CAIDI value as lambda, to determine the total CESIC per outage length seems to be a more adequate solution, estimating a yearly $2067,256 in losses for Vieques and Culebra residents, representing $375.93 in annual losses per customer household, with true costs of up to $0.36 /kWh if 400 kWh are being purchased at $0.28/kWh. Again, this method may underrepresent the impact on afflicted families. Hence, a more detailed approach may be necessary, as shown in the following table, which illustrates the necessity for granular data. The data described in Table 8 take the disaggregated SAIFI and SAIDI data from the NREL/LUMA study for a given interruption time period. While it assumes the minimum outage length per period, it shows the hourly CESIC and outage type estimates per period, yielding a minimum annual estimate of $1815,796 in residential losses for 5499 customers, $330.20 in annual household losses, and $0.35/kWh of true costs if consumption were 400 kWh a month purchased at $0.28/kWh.

Another finding is that the less energy a household consumes, the greater the VoLL and true costs of the electricity service. In the example in Table 8, if the household consumed an average monthly 500 kWh from the electric utility, instead of 400 kWh, the VoLL and true costs of the utility electric service would be reduced to $17.37/kWh and $0.34/kWh, respectively. However, if the household consumed 300 kWh per month, the VoLL and true costs would rise to$28.95/kWh and $0.38/kWh. Because income plays a role in our proposed methodology, it can be assumed that households with a high income would have a higher annual outage cost and VoLL value. Although the former is correct, the latter must also be closely observed. As previously mentioned, higher income has been correlated with higher consumption and WTP to avoid electricity outages (Munasinghe, 1980a). While the annual CESIC estimate is higher for a household with a higher income, its average annual consumption is inversely proportional to the VoLL estimate.

The proposed method could also be applied to estimate major events. For example, if we were to estimate the economic impact of Hurricane Fiona and the Costa Sur fault blackout from a macroeconomic perspective, such as that shown in Section 4.2, although we may be seeing the overall damage from a residential sector's perspective, we may be missing the actual impact on households. If we take the same three-member household example in Puerto Rico's western region, of which two were adults, and we discovered that they suffered 507.5 h of electric service interruption for Hurricane Fiona and 46.75 h of electric power interruption during the Costa Sur power plant fault blackout, the

Table 8
Outage cost estimation for Vieques and Culebra residential households (Siemens Industry, 2019b) via disaggregated CESIC estimation.

Outage Period	Minimum Outage Length in Period (Hrs.)	CESIC_H	CESIC per Outage Type
5 min–1 h	0.08	$ 0.03	$ 0.21
1–2 h	1	$ 0.39	$ 3.80
2–4 h	2	$ 0.79	$ 11.56
4–8 h	4	$ 2.75	$ 71.87
8–12 h	8	$ 5.79	$ 134.11
12–16 h	12	$ 9.42	$ 17.59
16–24 h	16	$ 13.94	$ 91.06
Total CESIC per Residential Customer			$ 330.20
Total per 5499 Residential Customers			$ 1815,796
VoLL per household			$19.07 / kWh
True Costs of Utility Serviced Electricity per household(with an average monthly consumption of 400 kWh purchased at utility rate of $0.28/kWh)			$ 0.35 / kWh

economic damage to their household would have been greater than the macroeconomic evaluation. Had this household not undertaken any mitigation and preparatory measures and only a single adult lived there instead of a family, the CESIC estimates in both events would have been approximately $21,877 and $2710.24, respectively. With a historical average consumption of 0.375 kW/h, the VoLL for this single-adult household during both blackouts would approximate a staggering $114.96/kWh to $154.60/kWh, compared to $1.15/kWh from the macroeconomic approach. While we feel it is important to understand how the overall economy can be affected from a broad or macro, yet impersonal perspective, the analysis would be incomplete if we do not provide a sense of the level of damage at the micro or household level. Further work is required for proper power outage calculations beyond the 24-h power outage length.

One of the central premises of this study is that time should be compensated for because it is a necessary component to produce goods. If customers can invest their time in household activities that have market value, then forgoing or wasting their time should be compensated. Although the proposed activities, goods, and services may differ in terms of both direct costs and weighted market cost of time, we feel that activities that are collectively considered necessary for human development will facilitate regulation and policymaking because part of the role of regulators and policymakers is to facilitate human development within the societies that they have been chosen to represent and serve. People must ensure clean clothing to avoid getting sick (hygiene), dishes to be washed, and houses to be kept clean for aseptic purposes. People must eat, communicate, sleep, and have time for leisure activities. Although leisure is necessary for productive human development, it is kept undefined for a reason. Some sectors may believe that fishing, hunting, or yachting are necessary activities for human development, whereas others may think the same of sports and fitness, moviegoing or fine dining, but not everyone will agree. Therefore, we recommend goods, services, and activities that are conventionally accepted as critical within any given region, which may vary in each region, at an average acceptable regional price.

One of the noteworthy findings of calculating the weighted cost of time is how this cost is reduced when people do not have proper sleep or have moments of leisure, as the lack of either reduces productivity. This raises a flag, as the impacts are numerically significant and shed light on the stark reality of many people who lack sleep and leisure time, particularly single working parents, who have little to no leisure time and reduced sleep time. Further study is required to understand the extent of their ramifications and how regulators and policymakers can provide aid to this sector of our society.

Comprehensively quantified CESICs within a stern regulatory framework can facilitate the discussion for necessary policy changes and potential grid-hardening or resiliency investments in lieu of requiring utilities to compensate customers for unreliable power grid operations. Several authors recognize the necessity of different types of grid-hardening investments that can be gleaned from CESIC calculations (Billinton et al., 1991; Gorman, 2022; Munasinghe and Sanghvi, 1988; Sanghvi, 1983) combined with other methods such as marginal substitution analysis (Anderson, 1972). Generation and bulk power system planning, T&D optimization, maintenance scheduling to levelize outage costs, design of rates, and cost-benefit evaluation of demand-side management programs, among other types of strategic planning, can be ascertained or benefitted from CESIC estimation. However, CESIC estimation may ultimately contribute to load defects when the reliability is not improved. When annual CESIC estimations are factored within utility-serviced cost evaluations, not only do the true costs better reflect the economic reality of the household, but our research also shows that the estimated time for a potential RES's return on investment is reduced when compared to the true cost of utility-purchased power with interruption costs. True cost estimates using an auxiliary generator are also higher when the costs of the time spent purchasing fuel are included in the overall fuel costs and customers are serviced by an unreliable power grid.

6. Conclusion

In this paper, we present a literature review of customer electric service interruption valuations and propose a market-based mathematical method for calculating hourly and annual CESICs. The results can be applied to calculate the CESIC of any country for which salaries and household activity occupation wage rates are available via the Internet. Our proposed household method includes both the direct and indirect costs associated with electric service interruptions via their interception as a risk assessment probabilistic approach subject to power outage times. The results yield minimum or low-bound outage costs, specifically for unprepared customers who have not taken mitigation measures. However, these results appear to correlate with studies using different methods undertaken in countries within the United States and the European Union, with monetary values adjusted to USD in November 2022 (see Table 9 and 10 in the Appendix).

Our proposed macroeconomic method can be applied to the residential sector by focusing on PCE rather than GDP, and it better isolates the economic impact of services that rely on electric power supply from services that do not need an electric power supply to operate.

The costs incurred when not having access to electric power shed light as to the value that access to electric power provides. Establishing the true energy costs for unreliable electric services is a key factor in customer decision-making when deciding whether to harden the grid or invest in household RESs. It can also serve as an indicator for electricity regulators to apply corrective actions to unreliable electric utilities, as it provides monetary value for grid unreliability. Energy burden (U.S. Department of Energy (DOE),(n.d.)) could even be rethought for unreliable power grids, by factoring outage costs within the percentage of household energy-related expenditures. The application of this method, through effective public policy, could potentially ensure a more reliable electric power grid as it entices the utility to improve its performance, lest they be required to compensate customers for unreliable electric service.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 9
Annual CESIC for Town Centers of Puerto Rico's 78 Municipalities with average household size of 2.8 members, of which 1.8 are assumed not formally employed. If Median Income is not available, we assume the benchmark (i.e. 2.8 members are not formally employed), True Cost of utility electric service were estimated using a $0.29/kWh electric utility residential service rate.

Municipal Town Center	Median Income	SAIDI	SAIFI	CAIDI	CESIC (CAIDI)	CESIC (CAIDI) Unemployed	CESIC Annual	CESIC CDF Annual	Average Annual Consumption	True Costs (CAIDI)	VoLL (CAIDI)	True Costs CDF	VoLL CFD
Puerto Rico Statewide	$ 30,472.00	27.44	7.52	3.72	$ 2.05	$ 1.10	$ 110.63	$ 427.70	4989	$ 0.30	$ 7.08	$ 0.37	$ 27.37
Adjuntas	$ 11,358.00	41.59	9.95	4.18	$ 2.89	$ 1.90	$ 262.76	$ 566.48	2665	$ 0.38	$ 20.77	$ 0.49	$ 44.77
Aguada	$ 9434.00	36.05	9.16	3.94	$ 1.52	$ 1.17	$ 130.36	$ 456.43	4022	$ 0.31	$ 7.88	$ 0.39	$ 27.58
Aguadilla	$ 9510.00	36.05	9.16	3.94	$ 1.52	$ 1.17	$ 130.44	$ 456.88	4345	$ 0.31	$ 7.30	$ 0.39	$ 25.55
Aguas Buenas	$ 17,875.00	26.88	5.58	4.82	$ 3.93	$ 2.21	$ 212.78	$ 437.98	4084	$ 0.33	$ 16.98	$ 0.39	$ 34.95
Aibonito	$ 16,706.00	17.72	4.79	3.70	$ 1.63	$ 1.09	$ 63.67	$ 232.48	3334	$ 0.30	$ 9.44	$ 0.35	$ 34.48
Añasco	$ 22,875.00	46.58	9.07	5.14	$ 4.68	$ 2.36	$ 416.12	$ 834.05	3976	$ 0.38	$ 19.68	$ 0.49	$ 39.45
Arecibo	$ 7675.00	21.01	7.00	3.00	$ 1.11	$ 0.89	$ 56.84	$ 201.13	4371	$ 0.29	$ 5.42	$ 0.33	$ 19.19
Arroyo	$ 10,389.00	18.86	8.88	2.12	$ 0.82	$ 0.62	$ 36.73	$ 127.87	4265	$ 0.29	$ 4.00	$ 0.31	$ 13.92
Barceloneta	$ -	21.01	7.00	3.00	$ -	$ 0.89	$ 52.17	$ 176.78	4585	$ 0.29	$ 4.74	$ 0.32	$ 16.07
Barranquitas	$ 12,862.00	26.44	5.74	4.61	$ 3.33	$ 2.11	$ 188.42	$ 393.88	3675	$ 0.33	$ 16.99	$ 0.39	$ 35.51
Bayamón	$ 10,177.00	24.52	7.32	3.35	$ 1.30	$ 0.99	$ 75.39	$ 270.57	5723	$ 0.29	$ 4.71	$ 0.33	$ 16.89
Cabo Rojo	$ 10,603.00	35.34	7.37	4.80	$ 3.27	$ 2.20	$ 255.38	$ 524.79	4135	$ 0.34	$ 15.31	$ 0.41	$ 31.46
Caguas	$ 16,746.00	26.88	5.58	4.82	$ 3.84	$ 2.21	$ 210.12	$ 432.11	5526	$ 0.32	$ 12.39	$ 0.36	$ 25.48
Camuy	$ 14,219.00	21.01	7.00	3.00	$ 1.26	$ 0.89	$ 60.07	$ 218.02	4136	$ 0.29	$ 6.06	$ 0.33	$ 21.98
Canóvanas	$ 28,107.00	24.11	7.58	3.18	$ 1.68	$ 0.94	$ 81.13	$ 309.41	5292	$ 0.30	$ 5.57	$ 0.34	$ 21.25
Carolina	$ 27,386.00	18.37	4.89	3.76	$ 1.98	$ 1.11	$ 73.08	$ 275.30	5849	$ 0.29	$ 5.96	$ 0.33	$ 22.44
Cataño	$ 14,717.00	24.05	6.48	3.71	$ 1.58	$ 1.10	$ 85.43	$ 309.13	6015	$ 0.29	$ 5.17	$ 0.33	$ 18.72
Cayey	$ 15,708.00	17.72	4.79	3.70	$ 1.60	$ 1.09	$ 63.16	$ 229.75	3935	$ 0.30	$ 7.94	$ 0.34	$ 28.87
Ceiba	$ 19,090.00	11.24	4.00	2.81	$ 1.28	$ 0.83	$ 31.18	$ 115.02	4804	$ 0.29	$ 5.06	$ 0.30	$ 18.65
Ciales	$ 14,236.00	27.78	6.86	4.05	$ 3.00	$ 1.84	$ 175.52	$ 382.59	3621	$ 0.33	$ 15.29	$ 0.39	$ 33.32
Cidra	$ 11,654.00	17.72	4.79	3.70	$ 1.48	$ 1.09	$ 61.07	$ 218.66	4116	$ 0.29	$ 7.34	$ 0.33	$ 26.27
Coamo	$ 10,926.00	21.60	5.01	4.31	$ 2.95	$ 1.97	$ 140.23	$ 299.57	4385	$ 0.31	$ 12.97	$ 0.35	$ 27.71
Comerío	$ 8105.00	26.44	5.74	4.61	$ 2.93	$ 2.11	$ 177.92	$ 370.33	3871	$ 0.33	$ 15.23	$ 0.38	$ 31.69
Corozal	$ 8500.00	37.69	11.14	3.38	$ 1.27	$ 1.00	$ 115.99	$ 411.23	4462	$ 0.31	$ 6.04	$ 0.37	$ 21.42
Culebra	$ 25,500.00	11.24	4.00	2.81	$ 1.42	$ 0.83	$ 32.76	$ 123.20	5689	$ 0.29	$ 4.49	$ 0.30	$ 16.87
Dorado	$ 17,331.00	29.36	7.97	3.68	$ 1.65	$ 1.09	$ 106.06	$ 386.74	8590	$ 0.29	$ 3.68	$ 0.33	$ 13.43
Fajardo	$ 14,852.00	11.24	4.00	2.81	$ 1.19	$ 0.83	$ 30.13	$ 109.61	4934	$ 0.29	$ 4.76	$ 0.30	$ 17.31
Florida	$ 20,221.00	21.01	7.00	3.00	$ 1.40	$ 0.89	$ 63.04	$ 233.51	4263	$ 0.29	$ 6.16	$ 0.33	$ 22.83
Guánica	$ 10,441.00	26.25	8.36	3.14	$ 1.23	$ 0.93	$ 75.98	$ 272.46	3158	$ 0.30	$ 8.03	$ 0.37	$ 28.80
Guayama	$ 14,112.00	18.86	8.88	2.12	$ 0.89	$ 0.62	$ 37.89	$ 133.46	4536	$ 0.29	$ 3.88	$ 0.31	$ 13.66
Guayanilla	$ 24,577.00	26.25	8.36	3.14	$ 1.58	$ 0.93	$ 85.11	$ 320.46	3754	$ 0.30	$ 7.57	$ 0.37	$ 28.49
Guaynabo	$ 47,397.00	27.01	6.88	3.93	$ 2.69	$ 1.16	$ 129.11	$ 509.08	8028	$ 0.30	$ 5.22	$ 0.34	$ 20.57
Gurabo	$ 9813.00	26.88	5.58	4.82	$ 3.23	$ 2.21	$ 193.77	$ 396.10	6330	$ 0.31	$ 9.98	$ 0.34	$ 20.39

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Table 9 (*continued*)

Municipal Town Center	Median Income	SAIDI	SAIFI	CAIDI	CESIC (CAIDI)	CESIC (CAIDI) Unemployed	CESIC Annual	CESIC CDF Annual	Average Annual Consumption	True Costs (CAIDI)	VoLL (CAIDI)	True Costs CDF	VoLL CFD
Hatillo	$ 14,122.00	16.41	4.10	4.00	$ 2.97	$ 1.83	$ 102.64	$ 223.44	4451	$ 0.30	$ 12.31	$ 0.33	$ 26.81
Hormigueros	$ 22,196.00	35.34	7.37	4.80	$ 4.28	$ 2.20	$ 291.05	$ 603.72	4097	$ 0.35	$ 17.61	$ 0.43	$ 36.53
Humacao	$ 12,928.00	34.62	8.30	4.17	$ 3.01	$ 1.90	$ 222.79	$ 480.28	5518	$ 0.32	$ 10.22	$ 0.37	$ 22.03
Isabela	$ 14,691.00	16.41	4.10	4.00	$ 3.01	$ 1.83	$ 103.31	$ 224.99	4116	$ 0.31	$ 13.40	$ 0.33	$ 29.19
Jayuya	$ 10,208.00	41.59	9.95	4.18	$ 2.80	$ 1.90	$ 259.16	$ 558.41	3056	$ 0.36	$ 17.86	$ 0.46	$ 38.49
Juana Díaz	$ 13,883.00	21.60	5.01	4.31	$ 3.18	$ 1.97	$ 145.20	$ 310.92	4895	$ 0.31	$ 12.03	$ 0.34	$ 25.77
Juncos	$ 12,772.00	34.62	8.30	4.17	$ 3.00	$ 1.90	$ 222.38	$ 479.35	4832	$ 0.33	$ 11.65	$ 0.38	$ 25.10
Lajas	$ -	35.34	7.37	4.80	$ -	$ 2.20	$ 217.33	$ 440.61	3791	$ 0.34	$ 14.21	$ 0.40	$ 28.80
Lares	$ 13,364.00	33.32	8.45	3.94	$ 1.64	$ 1.17	$ 124.58	$ 444.13	3053	$ 0.32	$ 10.73	$ 0.43	$ 38.25
Las Marías	$ 38,333.00	33.32	8.45	3.94	$ 2.42	$ 1.17	$ 150.55	$ 580.79	2995	$ 0.33	$ 13.21	$ 0.47	$ 50.98
Las Piedras	$ 10,818.00	34.62	8.30	4.17	$ 2.85	$ 1.90	$ 217.30	$ 467.66	4737	$ 0.33	$ 11.61	$ 0.38	$ 24.98
Loíza	$ 12,379.00	24.11	7.58	3.18	$ 1.29	$ 0.94	$ 71.69	$ 259.64	4234	$ 0.30	$ 6.15	$ 0.34	$ 22.28
Luquillo	$ -	11.24	4.00	2.81	$ -	$ 0.83	$ 26.04	$ 88.40	4901	$ 0.29	$ 4.14	$ 0.30	$ 14.05
Manatí	$ 10,359.00	27.78	6.86	4.05	$ 2.72	$ 1.84	$ 167.70	$ 364.46	4771	$ 0.32	$ 11.08	$ 0.36	$ 24.09
Maricao	$ 11,953.00	46.58	9.07	5.14	$ 3.65	$ 2.36	$ 368.31	$ 731.67	2466	$ 0.43	$ 28.09	$ 0.58	$ 55.80
Maunabo	$ 21,023.00	18.86	8.88	2.12	$ 1.00	$ 0.62	$ 40.04	$ 143.84	3608	$ 0.29	$ 5.15	$ 0.32	$ 18.52
Mayagüez	$ 5786.00	46.58	9.07	5.14	$ 3.07	$ 2.36	$ 341.32	$ 673.86	4061	$ 0.36	$ 15.80	$ 0.45	$ 31.20
Moca	$ -	36.05	9.16	3.94	$ -	$ 1.17	$ 117.76	$ 390.27	3777	$ 0.31	$ 7.58	$ 0.38	$ 25.11
Morovis	$ 11,029.00	27.78	6.86	4.05	$ 2.77	$ 1.84	$ 169.05	$ 367.59	4300	$ 0.32	$ 12.40	$ 0.37	$ 26.96
Naguabo	$ 15,712.00	34.62	8.30	4.17	$ 3.22	$ 1.90	$ 230.03	$ 496.93	4510	$ 0.33	$ 12.91	$ 0.39	$ 27.88
Naranjito	$ 5505.00	24.52	7.32	3.35	$ 1.18	$ 0.99	$ 72.39	$ 254.64	4426	$ 0.30	$ 5.84	$ 0.34	$ 20.56
Orocovis	$ 19,514.00	26.44	5.74	4.61	$ 3.89	$ 2.11	$ 203.10	$ 426.80	3066	$ 0.35	$ 21.95	$ 0.42	$ 46.12
Patillas	$ 11,881.00	18.86	8.88	2.12	$ 0.85	$ 0.62	$ 37.20	$ 130.11	3885	$ 0.29	$ 4.45	$ 0.31	$ 15.56
Peñuelas	$ 14,665.00	20.30	6.20	3.27	$ 1.39	$ 0.97	$ 63.51	$ 231.51	4027	$ 0.30	$ 6.81	$ 0.34	$ 24.81
Ponce	$ 9651.00	20.30	6.20	3.27	$ 1.26	$ 0.97	$ 60.89	$ 217.70	4942	$ 0.29	$ 5.32	$ 0.32	$ 19.01
Quebradillas	$ 9455.00	16.41	4.10	4.00	$ 2.63	$ 1.83	$ 97.13	$ 210.69	3928	$ 0.30	$ 13.21	$ 0.33	$ 28.64
Rincón	$ 20,158.00	36.05	9.16	3.94	$ 1.85	$ 1.17	$ 142.42	$ 519.81	4520	$ 0.31	$ 7.66	$ 0.39	$ 27.95
Río Grande	$ 16,989.00	24.11	7.58	3.18	$ 1.40	$ 0.94	$ 74.46	$ 274.23	5314	$ 0.29	$ 5.09	$ 0.33	$ 18.75
Sabana Grande	$ 12,817.00	35.34	7.37	4.80	$ 3.47	$ 2.20	$ 262.19	$ 539.87	3548	$ 0.35	$ 18.32	$ 0.43	$ 37.72
Salinas	$ 16,297.00	18.86	8.88	2.12	$ 0.92	$ 0.62	$ 38.57	$ 136.74	4391	$ 0.29	$ 4.08	$ 0.31	$ 14.46
San Germán	$ 9782.00	35.34	7.37	4.80	$ 3.20	$ 2.20	$ 252.85	$ 519.20	3606	$ 0.35	$ 17.38	$ 0.42	$ 35.69
San Juan	$ 26,997.00	27.01	6.88	3.93	$ 2.06	$ 1.16	$ 112.00	$ 418.94	6111	$ 0.30	$ 5.94	$ 0.35	$ 22.23
San Lorenzo	$ 12,283.00	26.88	5.58	4.82	$ 3.44	$ 2.21	$ 199.59	$ 408.93	4252	$ 0.33	$ 15.30	$ 0.38	$ 31.34
San Sebastián	$ 13,837.00	33.32	8.45	3.94	$ 1.65	$ 1.17	$ 125.07	$ 446.72	3507	$ 0.32	$ 9.38	$ 0.41	$ 33.49
Santa Isabel	$ 18,764.00	21.60	5.01	4.31	$ 3.56	$ 1.97	$ 153.38	$ 329.65	5157	$ 0.31	$ 12.06	$ 0.34	$ 25.93
Toa Alta	$ 18,371.00	37.69	11.14	3.38	$ 1.54	$ 1.00	$ 125.91	$ 463.56	6852	$ 0.30	$ 4.27	$ 0.35	$ 15.72
Toa Baja	$ 9782.00	35.34	7.37	4.80	$ 3.20	$ 2.20	$ 252.85	$ 519.20	5664	$ 0.32	$ 11.07	$ 0.37	$ 22.72

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Table 9 (*continued*)

Municipal Town Center	Median Income	SAIDI	SAIFI	CAIDI	CESIC (CAIDI)	CESIC (CAIDI) Unemployed	CESIC Annual	CESIC CDF Annual	Average Annual Consumption	True Costs (CAIDI)	VoLL (CAIDI)	True Costs CDF	VoLL CFD
Trujillo Alto	$ 16,675.00	43.16	17.18	2.51	$ 1.10	$ 0.74	$ 104.70	$ 379.74	6118	$ 0.30	$ 3.47	$ 0.34	$ 12.60
Utuado	$ 9337.00	41.59	9.95	4.18	$ 2.74	$ 1.90	$ 256.44	$ 552.14	3090	$ 0.36	$ 17.48	$ 0.46	$ 37.64
Vega Alta	$ 10,682.00	29.36	7.97	3.68	$ 1.45	$ 1.09	$ 100.38	$ 356.72	5456	$ 0.30	$ 5.49	$ 0.35	$ 19.50
Vega Baja	$ 15,208.00	29.36	7.97	3.68	$ 1.59	$ 1.09	$ 104.25	$ 377.16	4884	$ 0.30	$ 6.37	$ 0.36	$ 23.04
Vieques	$ 7383.00	11.24	4.00	2.81	$ 1.03	$ 0.83	$ 28.29	$ 100.07	4774	$ 0.29	$ 4.62	$ 0.30	$ 16.33
Villalba	$ 11,169.00	21.60	5.01	4.31	$ 2.97	$ 1.97	$ 140.64	$ 300.50	4138	$ 0.31	$ 13.79	$ 0.35	$ 29.45
Yabucoa	$ 14,459.00	34.62	8.30	4.17	$ 3.12	$ 1.90	$ 226.77	$ 489.44	3825	$ 0.34	$ 15.00	$ 0.41	$ 32.38
Yauco	$ 12,328.00	26.25	8.36	3.14	$ 1.27	$ 0.93	$ 77.20	$ 278.87	3621	$ 0.30	$ 7.11	$ 0.36	$ 25.70

Table 10
Outage Cost Estimation Studies in different parts of the World.

Country	Evaluation Method	Year	Unit	USD Nov 2022	Study
Brazil	WTP - Low Income Based Analysis WTP - Low to Medium Income Based Analysis LM WTP - Upper Medium Income Based Analysis WTP - Upper Income Based Analysis U	1976	$/h	$ 16.82 $ 16.87 $ 16.78 $ 19.55	(Munasinghe, 1980a)
US	WTP, forgone leisure	1981	$/h	$ 0.79 $ 0.86 $ 0.96 $ 1.03 $ 1.98	(Sanghvi, 1982)
Canada	Sector Customer Damage Function (SCDF)	1991	$/h	$ 0.10 $ 0.42 $ 2.50	(Wacker and Tollefson, 1994)
Denmark Finland Iceland	WTP	1995	$/h	$ 4.95 $ 1.58 $ 2.77	(Lehtonen and Lemstrom, 1995)
Nepal	Survey - Preparatory Action Approach	1996	$/h	$ 0.34 $ 0.43 $ 0.44 $ 0.53	(Pandey and Billinton, 1999)
Hong Kong	Macroeconomic - Relational Approach - household income	1996	$/h	$ 11.61	(Mok and Chung, 1997)
South Korea		1999	$/h	$ 2.49	(Choi et al., 2002)
Netherlands	Survey - VOLL	2001	$/kWh	$ 24.95	(Reichl et al., 2013)
Norway	Direct Worth combined with WTP	2002	$/h	$ 1.82	(KjØlle et al., 2008)
Finland	Unexpected Outages – Mathematical and Macroeconomic Planned Outages – Mathematical and Macroeconomic	2005	$/h	$ 21.37 $ 13.21	(Gündüz et al., 2018)
Germany	Macroeconomic WTP/WTA	2007	$/h	$ 17.14	(Praktiknjo et al., 2011)
Spain	Survey - VOLL	2008	$/kWh	$ 11.76	(Linares and Rey, 2013)
South Africa	Direct Worth combined with WTP	2008	$/h	$ 5.80 $ 4.17 $ 3.94 $ 5.50	(Herman, 2008)
Netherlands	Survey - One outage per Year VOLL Valuation of power grid reliability.	2009	$/kWh	$ 6.68 $ 9.83 $ 7.67 $ 3.73 $ 1.57	(Baarsma and Hop, 2009)
Austria	Survey - VOLL	2011	$/kWh	$ 2.26	(Reichl et al., 2013)
Germany	Survey - WTP Survey - WTA	2011	$/h	$ 27.97 $ 63.31	(Praktiknjo, 2014)
US	Survey - MISO - VOLL - meta-database of Berkeley National Lab survey results of Midwest Region	2012	$/kWh	$ 2.27	(London Economics International LLC, 2013)
Austria	VOLL - survey	2012	$/kWh	$ 2.36 $ 6.40 $ 16.67 $ 29.13	
New Zealand Australia - Victoria	Robust Survey - VOLL	2012	$/kWh	$ 8.88 $ 14.85	
Republic of Ireland	Macroeconomic, with some survey data - VOLL - For the residential sector, survey data on intraday, hourly residential activities was used in combination with assumed monetary values representing opportunity costs for various residential activities	2012	$/kWh	$ 23.54	

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Table 10 (*continued*)

Country	Evaluation Method	Year	Unit	USD Nov 2022	Study
Austria	Macroeconomic - sensitivity analysis of 'substitutability factor' – the proportion of leisure activities that are electricity-dependent.	2013	$/kWh	$ 17.16	(Shivakumara et al., 2017)
Belgium				$ 25.29	
Bulgaria				$ 2.70	
Croatia				$ 6.89	
Cyprus				$ 10.38	
Czech Republic				$ 7.66	
Denmark				$ 26.95	
Estonia				$ 7.30	
Finland				$ 9.37	
France				$ 15.25	
Germany				$ 22.34	
Greece				$ 8.74	
Hungary				$ 7.61	
Ireland				$ 20.07	
Italy				$ 28.55	
Latvia				$ 7.76	
Lithuania				$ 23.83	
Luxembourg				$ 25.16	
Malta				$ 9.57	
Netherlands				$ 29.49	
Poland				$ 11.60	
Portugal				$ 11.97	
Romania				$ 8.18	
Slovakia				$ 10.59	
Slovenia				$ 10.69	
Spain				$ 14.13	
Sweden				$ 11.26	
United Kingdom				$ 13.85	
Romania	WTP Survey: Low-Reliability (5.4 Outages in 2012) - Winter - (2016) Cohena, Moeltner, Reichl, Schmidthaler	2013	$/h	$ 5.89	(Cohen et al., 2016)
Bulgaria	WTP Survey: Low-Reliability (4.8 Outages in 2012) - Winter			$ 5.62	
Greece	WTP Survey: Low-Reliability (3.8 Outages in 2012) - Winter			$ 4.29	
Hungary	WTP Survey: Low-Reliability (3.2 Outages in 2012) - Winter			$ 5.47	
Poland	WTP Survey: Low-Reliability (3.1 Outages in 2012) - Winter			$ 6.84	
Finland	WTP Survey: Medium-Reliability (2.4 Outages in 2012) - Winter			$ 5.41	
Slovenia	WTP Survey: Medium-Reliability (2.2 Outages in 2012) - Winter			$ 4.76	
Spain	WTP Survey: Medium-Reliability (2.2 Outages in 2012) - Winter			$ 3.78	
Estonia	WTP Survey: Medium-Reliability (2.1 Outages in 2012) - Winter			$ 3.15	
France	WTP Survey: Medium-Reliability (2.0 Outages in 2012) - Winter			$ 0.62	
Sweden	WTP Survey: High-Reliability (1.2 Outages in 2012) - Winter			$ 3.27	
Denmark	WTP Survey: High-Reliability (1.1 Outages in 2012) - Winter			$ 6.84	
Ireland	WTP Survey: High-Reliability (0.9 Outages in 2012) - Winter			$ 6.16	
Netherlands	WTP Survey: High-Reliability (0.8 Outages in 2012) - Winter			$ 3.59	
Germany	WTP Survey: High-Reliability (0.7 Outages in 2012) - Winter			$ 1.77	
Romania	WTP Survey: Low-Reliability (5.4 Outages in 2012) - Summer			$ 1.23	
Bulgaria	WTP Survey: Low-Reliability (4.8 Outages in 2012) - Summer			$ 0.55	
Greece	WTP Survey: Low-Reliability (3.8 Outages in 2012) - Summer			$ 0.83	
Hungary	WTP Survey: Low-Reliability (3.2 Outages in 2012) - Summer			$ 1.24	
Poland	WTP Survey: Low-Reliability (3.1 Outages in 2012) - Summer			$ 1.89	
Finland	WTP Survey: Medium-Reliability (2.4 Outages in 2012) - Summer			$ 0.92	
Slovenia	WTP Survey: Medium-Reliability (2.2 Outages in 2012) - Summer			$ 0.62	
Spain	WTP Survey: Medium-Reliability (2.2 Outages in 2012) - Summer			$ 0.15	
Estonia	WTP Survey: Medium-Reliability (2.1 Outages in 2012) - Summer			$ 0.21	
France	WTP Survey: Medium-Reliability (2.0 Outages in 2012) - Summer			$ (0.76)	
Sweden	WTP Survey: High-Reliability (1.2 Outages in 2012) - Summer			$ 0.58	
Denmark	WTP Survey: High-Reliability (1.1 Outages in 2012) - Summer			$ 1.58	
Ireland	WTP Survey: High-Reliability (0.9 Outages in 2012) - Summer			$ 0.98	
Netherlands	WTP Survey: High-Reliability (0.8 Outages in 2012) - Summer			$ 0.59	
Germany	WTP Survey: High-Reliability (0.7 Outages in 2012) - Summer			$ 0.50	
Finland	WTP	2015	$/h	$ 11.00	(Küfeoğlu and Lehtonen, 2015a)
China	Production Theory - Parametric Distance function Marginal Costs incurred to reduce power outage time	2017	$/kWh	$ 2.05 $ 0.87 $ 2.10 $ 1.51	(Chen et al., 2021)
Sweden	WTP - Planned Outage	2017	$/h	$ 3.68 $ 3.26 $ 2.82	(Carlsson et al., 2021)
	WTP - Unplanned Outage			$ 4.19 $ 3.86 $ 3.18	

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