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**Electricity deficit cost estimation in Brazil by applying input-output
analysis**

São Paulo

2018

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Dissertation Presented to the Polytechnic School
of the University of São Paulo, Brazil, in Partial
Fulfillment of the Requirements for the
Production Engineering Master of Science's
Degree.

Advisor: Prof. Dr. Erik Eduardo Rego.

São Paulo

2018

Este exemplar foi revisado e corrigido em relação à versão original, sob responsabilidade única do autor e com a anuência de seu orientador.

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Catálogo-na-publicação

Martins, Lilian Maluf

Electricity deficit cost estimation in Brazil by applying input-output analysis / L. M. Martins -- versão corr. -- São Paulo, 2018.
98 p.

Dissertação (Mestrado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Produção.

1.Planejamento energético 2.Insumo-produto 3.Produto interno bruto
I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia de Produção II.t.

ACKNOWLEDGEMENTS

First, I want to thank Erik Rego for opening some of the most important doors in my professional and academic life.

Second, Gabriel Alberto, who demonstrated much interest in my research, extensively listening to and debating several aspects of it, and whose opinions have certainly improved my work.

I am also grateful to those who have directly contributed to my work or from whom I have learned important content during my research: Eduardo Amaral Haddad, Marina Camargo Henriques, Érico Henrique Garcia de Brito, Fernando Almeida Prado and Dorel Soares Ramos.

I am very grateful to Elaine and Josias for teaching me the importance of education, being themselves solid examples of endurance. The developmental environment they provided built in me the motivation to prioritize this work until its conclusion.

Finally, I thank all those who in some way spent time with me during this research: my family, co-workers and friends, especially Sandra Xavier, who happened to lead me into my first steps in the academic research world.

ABSTRACT

MARTINS, L. M. **Electricity Deficit Cost Estimation in Brazil by Applying Input-Output Analysis**. 2018. 98 p. Dissertation (Production Engineering Master of Science) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2018.

The supply chain risk management discipline studies how to address daily and extraordinary risks to avoid vulnerability and to guarantee production continuity. In the case of the electricity sector, the economic impact of interrupting the power supply is depicted by an indicator called the deficit cost, measured in monetary unit per electricity consumption unit (for example, in Brazil, R\$/MWh). This value is commonly applied to cost-benefit analysis that results in decisions about maintenance and investment in the electricity system in the medium and long term, in addition to composing the short-term energy price. Most countries in the world have a thermal energy matrix, and cases in which interruption problems occur are mainly due to punctual failures in generation or transmission and last a few hours or days until maintenance is concluded. Brazil, however, has been strongly dependent on hydrological conditions ever since the main generation source became hydroelectric. Since restricted energy supply scenarios last longer, from weeks to months, a better measure for the electricity structural deficit impact is the economic loss in the deficit-affected regional production, translated as the GDP (gross domestic product) region. This dissertation estimates the Brazilian GDP marginal loss due to power deficits by applying an input-output (I/O) matrix analysis methodology and concludes that the officially adopted deficit cost is underestimated.

Keywords: deficit cost; outage cost; electricity; input-output; GDP; Brazil.

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LIST OF ABBREVIATIONS

ABEGAS	Brazilian Piped Gas Association
ANEEL	Brazilian Agency of Electric Power
ANP	National Agency of Petroleum and Gas
BEN	National Energetic Balance
BRL	Brazilian Real (currency)
CBA	Cost Benefit Analysis
CCEE	Electric Power Trading Chamber
CCPE	Expansion Planning Committee Coordinator
CEDEF	Explicit Deficit Cost
CEPEL	Electricity Research Center
CME	Expansion Marginal Cost
CMO	Operation Marginal Cost
CMSE	Electric Sector Monitoring Committee
CNPE	National Council for Energy Policy
CTEM	Market Study Technical Committee
CVM	Contingent Valuation Method
DPE	Energetic Planning Department
EIOT	Energy Input-Output Table
ELETROBRÁS	Brazilian Electric Power Company
EPE	Energy Research Company
EUR	Euro (currency)
FGV	Getúlio Vargas Foundation
GCE	Electricity Crisis Management Chamber
GCPS	Power System Planning Coordinating Group
GDP	Gross Domestic Product
GWh	Giga-watt hour (electricity consumption unit)
IBGE	Brazilian Institute of Geography and Statistics
IEA	International Energy Agency
IGP-DI	General Price Index – Intern Availability

IGP-M	General Price Index – Market
I/O	Input-output
IPCA	Extended Consumer Price Index
IPEA	Applied Economic Research Institute
MAE	Electricity Wholesaler Market
MIOT	Monetary Input-output Table
MME	Ministry of Mining and Energy
MWa	Mega-watt average
MWh	Mega-watt hour (electricity consumption unit)
N	North
NAS	National Account Systems
NE	Northeast
ONS	National Brazilian System Operator
PIOT	Physical Input-output Table
RC	Charge Reduction
R&D	Research and Development
R\$	Brazilian Real (currency)
S	South
SE / CO	Southeast / Midwest
SIM	Market Integrated System Report
SIN	Brazilian Interconnected National System
SUISHI-O	Simulation model of individualized hydropower plants in interconnected systems
TEC	Total Electricity Consumption
TWh	Tera-watt hour (electricity consumption unit)
U.S.	United States of America
USD	U.S. Dollar (currency)
VoLL	Value of Lost Load
WTP	Willingness to Pay
WTA	Willingness to Accept

1 INTRODUCTION

As electricity has become increasingly important to the daily activities of people throughout the world, its supply continuity and reliability is of major importance. Many studies focus on the reliability of electrical components to make systems technically robust using appropriate technologies. Economics may sustain that technical reliability by permitting the economic feasibility of each technology that is applied and by giving electricity consumers confidence that the system may support the demand without failing due to a lack of capacity in generation or transmission.

This dissertation regards the following economic issue: how to price the deficit risk so that the electricity demand does not surpass the system capacity or so that the system capacity grows sufficiently to supply the demand before a deficit occurs.

As further explained, the calculations regard the National Interconnected Energy System (SIN – Brazilian acronym) and do not consider the independent power supply system areas.

The Introduction Subsection 1.1 contextualizes the electricity sector of Brazil. Subsection 1.2 explains the justification and motivations of this work, and Subsection 1.3 summarizes the objectives. Subsection 1.4 presents the research method adopted, and finally, Subsection 1.5 provides the dissertation structure.

1.1 THE BRAZILIAN ELECTRICITY SECTOR

Brazil is over 8 million square kilometers in area, with very diverse rural and urban regions that have different climatic seasonal behaviors. To orchestrate such a complex electricity supply, a computational software that simulates the Brazilian electricity sector is used to model 5 years ahead of the provision of services and comprises both operation, including power plant dispatch needs, and electricity price, always aiming to minimize operational costs. The deficit cost is an important extrinsically calculated input for those simulations.

The power plant park, operated by the National Brazilian System Operator (ONS – Brazilian acronym), is primarily composed of hydro source power, which represents 61% of the total installed capacity, while thermoelectric power represents 26%, which is divided into

almost 9% originating from biomass fuel, 8% from natural gas and approximately 9% from other fossil and thermonuclear fuels (AGENCIA NACIONAL DE ENERGIA ELÉTRICA, 2017). Completing the electricity fuel matrix, 7% of the electricity sources are generated by wind, 5% are imported, and finally, less than 1% are generated by solar power. This means that intermittent fuel represents 77% of the Brazilian total power plant park capacity.

There are other countries where water represents more than 50% of the national electricity source. Those among the top-ten hydropower producers, in addition to Brazil, are Canada, Norway, and Venezuela, with 2017 production values of 381 TWh, 139 TWh and 75 TWh, respectively, while Brazil produced 360 TWh (INTERNATIONAL ENERGY AGENCY, 2017).

Figure 1 compares the Brazilian source matrix of electricity production to the world, in which thermo fuels originate more than half of the total electricity production. Only 16% of the world electricity production originated from hydro in 2017, while thermopower sources were responsible for approximately 71% of the total production.

Due to the difference in the Brazilian major sources in the matrix compared to those of other countries, the present dissertation suggests different deficit cost estimation methodologies than those observed on the international bibliographic review. The methodology choice depends on the matrix source composition issue and is better explained in Section 2.8, which presents the Brazilian context.

The SIN reaches most but not all the population. There is a region without transmission lines to interconnect the whole country. These areas have independent power supply systems subsidized by the SIN consumers. This dissertation focuses only on SIN.

The Brazilian SIN is divided into four energy submarkets as follows: southeast/middle-east (SE/CO), south (S), northeast (NE) and north (N). Each submarket is defined by electrical proximity and separated by important transmission lines that represent few interconnection channels between submarkets. If a submarket cannot integrally supply its demand, or if there is cheaper energy production in a neighboring submarket that has a plentiful supply at the moment, energy can be imported/exported between submarkets, respecting transmission limits. These transmission restrictions result in different short-term energy prices between submarkets. Figure 2 represents transmission interconnections in SIN, and Figure 3, the four SIN submarket divisions.

Figure 1 - Electricity production by source in 2017.

Source: the author, based on the Brazilian Agency of Electric Power (ANEEL) for the Brazilian data and on the International Energy Agency (IEA) for the world data (AGENCIA NACIONAL DE ENERGIA ELÉTRICA, 2017; INTERNATIONAL ENERGY AGENCY, 2017).

Figure 2 - Brazilian Interconnected National System (SIN) in 2017.

Source: AGENCIA NACIONAL DE ENERGIA ELÉTRICA (2017).

Figure 3 - SIN submarket divisions.

Source: Adapted from the Electric Power Trading Chamber (CCEE – Brazilian acronym).

The main official Brazilian entities that manage, control, and govern the electricity sector are the following:

- Ministry of Mining and Energy (MME – Brazilian acronym);
- National Council for Energy Policy (CNPE – Brazilian acronym);
- Brazilian Agency of Electric Power (ANEEL – Brazilian acronym);
- National Brazilian System Operator (ONS – Brazilian acronym);
- Electric Power Trading Chamber (CCEE – Brazilian acronym);
- Energy Research Company (EPE – Brazilian acronym); and
- Electric Sector Monitoring Committee (CMSE – Brazilian acronym).

Figure 4 shows the interrelation between these entities.

Figure 4 – Main official entities in the Brazilian electricity sector.

Source: the author based on MME data (MINISTÉRIO DE MINAS E ENERGIA, 2017).

The bibliographic review in Section 2 details the official agent regulatory acts regarding the deficit cost. So far, no solution has been considered fully satisfactory to be officially adopted as a national deficit cost estimation methodology. The current value used is considered temporary, although it was calculated in 1988 and since then updated by the inflation and monetary exchange rate. In 1988, an input-output matrix analysis was used, the data of which do not consider changes in electricity use due to efficiency initiatives adopted in the 2001 rationing episode and natural technology improvements in productive sectors. Published data have changed, and input-output analysis studies have improved since the 1988 estimation; the theme is thus still a study subject, including an ANEEL R&D project currently under development with the same aim as this dissertation: suggest a new calculation methodology.

1.2 JUSTIFICATION AND MOTIVATION

Most countries in the world have a thermal energy matrix; interruption problems occur mainly due to punctual failures in generation or transmission and last a few hours or days until maintenance is concluded. During that time, consumers may have losses due to the lack

of electricity supply, and to measure the losses, the application of surveys questioning the value of losses or willingness to pay or to receive payment depending on service availability is very common. This does not occur in Brazil because it has had a strong dependence on hydrological conditions ever since the main generation source became hydroelectric. Power interruption problems occur mainly because of structural problems in supply, namely, a power generation capacity that is lower than demand, which means expansion programming requires special attention and reservoir capacity considerations, hydrological provisions, or alternative source possibilities. Since deficits last longer, sometimes for months instead of a few hours or days, a better measure for the structural electricity deficit impact is the economic loss in production for the affected region. The indicator for the production of a region is the GDP (gross domestic product); a GDP decrease in productive sectors due to a lack of energy is thus a well-accepted measure of structural deficits; therefore, measuring the consequent GDP variation is the main approach chosen for this research.

In 2001, Brazil faced a serious electricity rationing episode due to the lack of planning and investments (PRESIDENCY, 2001). Under those poor hydrologic conditions, the system could not supply the demand, and increased attention was focused on the deficit cost topic at the time.

The discomfort of the consumers and the great effort demanded from the distributors and the sectoral entities may be illustrated by the fact that 94 resolutions were published in 2001 by the Electricity Crisis Management Chamber (GCE – Brazilian acronym). GCE resolution n. 4 (2001) established consumption targets that varied from 75% to 100% of the previous 3-month average consumption, depending on the consumer type and the contracted demand. There were bonuses credited on the next bill proportional to the difference between the attained underconsumption and the target.

On the other hand, there were also penalties to stimulate the reduction; for example, GCE resolution n. 4 (2001) established an increase of 50% on the tariff applied to residential consumers for the consumption of between 200 and 500 kWh, and a 200% additional tariff was applied for the consumption of over 500 kWh. GCE resolution n. 22 (2001) imposed a supply suspension for those consumer units that surpassed the target consumption; for example, there was a written notification delivered to residential consumers following the first

occurrence, and when recurrent, a suspension of one day was given for every one percent of the surpassed consumption target.

1.3 OBJECTIVE

In Brazil, the deficit cost is an extrinsically calculated input for analysis that results in electricity system expansion and operation decisions. This dissertation aims to estimate the Brazilian GDP loss due to the lack of electricity supply as a proxy of the electricity deficit cost.

The main hypothesis is that there are possibilities to improve the current official estimate, and since the current estimate approach is based on input-output (I/O) analysis, this research objective is to verify improvement possibilities by using the same official approach.

Nevertheless, to achieve the main objective, some secondary objectives are outlined. The first is to ascertain the importance of the estimated value by observing the possible applications cited in the literature. Another secondary objective is to review the commonly applied international methodologies and then to search for alternative initiatives to estimate the electricity deficit cost in Brazil.

Finally, the objective of analyzing or testing ideas other than the official I/O approach is aimed to certify which approach may be more adequate and develop or improve the existing methodologies. By following these objectives, in addition to the I/O analysis, a simple regression of GDP over electricity is also explored.

1.4 METHODS

This research is exploratory, in which the hypothetico-deductive method is chosen. The gap explored is the electricity deficit cost calculation in Brazil that has not been reviewed since 1988. The research begins with an international bibliographic review aiming to determine the methodologies applied world-wide. In sequence, the Brazilian history of the study field is researched, and the previously developed methodologies applied to the country are critically analyzed. Enlightened by this knowledge, including the critical analysis performed by this dissertation author, the methodologies, or the parts that seem meaningful, are reproduced considering updates and enhancements or innovations.

Hence, two methodologies are applied to each year from 2003 to 2013 to observe the result evolution throughout the period. The first methodology is a linear regression of GDP over electricity consumption. Ipeadata (2017) is the source for GDP data, and the Annual Energy Balance published by EPE (2017) is the source for electricity consumption.

The second methodology is the I/O analysis for the same period (2003 to 2013) that uses the I/O matrix data developed by Guilhoto and Filho (2005; 2010) based on the Geography and Statistics Brazilian Institute (IBGE – Brazilian acronym) resources and uses tables data (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2017).

A critical evaluation of the estimated deficit cost obtained by each methodology and scenario is made to lead to the conclusion that suggests the more adequate choice of those methodologies.

1.5 DISSERTATION STRUCTURE

Chapter 2 presents a bibliographic review of electricity deficit cost based on approaches from international state-of-the-art and Brazilian initiatives, including governmental and independent studies.

In Chapter 3, Brazilian methodologies proposed and found in the bibliographic review are carefully and critically analyzed. Additionally, an improved electricity consumption and GDP regression methodology and a deficit cost estimation methodology using an input-output approach are proposed.

Chapter 4 analyzes the sensitivity of the results due to different electricity rationing distributions among the economically productive sectors. The method that is considered more adequate is then applied to the years from 2003 to 2013. Finally, there is a comparison between the results obtained by the proposed methodology and the official number adopted for those years.

Chapter 5 concludes by summarizing the work results and suggesting future content development possibilities.

2 BIBLIOGRAPHIC REVIEW

A lack of electricity supply may occur in cases where outages are derived from net failures, a lack of thermal fuel, or cases of structural deficit. In a country where the electricity supply matrix is mainly composed of hydropower generation, a structural deficit may be characterized during periods of critical hydrology when hydropower plant generation capacity decreases, which is the case for Brazil.

Depending on the case, the outage or deficit duration changes significantly; in the case of a lack of fuel or punctual net failure, the supply problem can be solved in a few hours by providing maintenance or fuel or by dispatching another thermal powerplant. In the case of a bad hydrological scenario and system capacity issues, the supply level may take months to normalize.

The first 7 sections of Chapter 2 (from Section 2.1 to Section 2.7) present a non-Brazilian bibliographic review, and Section 2.8 presents a Brazilian bibliographic review. The non-Brazilian studies heavily use survey techniques applied to consumers, while the Brazilian studies focus on GDP loss due to a lack of energy and methodologies that associate electricity consumption and GDP variation, mainly by input-output or regression analysis. In addition, most international studies highlight the significance of cost drivers used to compose the deficit cost and the consequent relevance of the sensitivity analysis; consequently, Subsection 2.4 exclusively approaches the cost driver issue.

Section 2.1 approaches the applicability of deficit cost in sector decisions and energy prices, while Section 2.2 contextualizes the deficit cost as one aspect of energy supply security. Section 2.3 describes the estimation methodologies commonly used and tries to group them by classifying the methods by similarity. As previously cited, Section 2.4 lists some of the cost drivers that are used in sensitivity analysis in several cases. Section 2.5 gathers some of the cost deficit aspects that, despite not being commonly cited in articles, were considered relevant to complement this bibliographic review. Section 2.6 presents a summarized comparative table of some of the international study results to demonstrate the absence of a pattern for calculation procedures and the resulting deficit costs regarding the

measurement units and data assumptions. Section 2.7 presents some improvements suggested by the studies presented in previous sections.

As already cited, a Brazilian bibliographic review is presented next, in Section 2.8, focusing on the more commonly encountered national approaches of linear regression of GDP over electricity consumption and I/O analysis.

2.1 APPLICABILITY

Some of the deficit cost applicability cited by the international studies consulted is summarized in the present section. Decisions about maintenance and investments and decisions about which regions and sectors should be cut off during electricity restriction periods can be made based on the electricity deficit cost. Moreover, it may be important to consider the risk and valuation of the deficit cost in the composition of the energy price, aiming to give the right price signal to consumers to avoid difficult restriction situations.

The following bullets briefly comment on those applicabilities:

- **Decisions about maintenance and investments**

Reichl et al. (2013) said that knowing the value of electricity supply security is necessary to make efficient infrastructure investment decisions. Ozbaflı and Jenkins (2016) apply a cost benefit analysis (CBA), using the outage cost reflected by consumer willingness to pay (WTP) for a reliable electricity supply, to suggest the purchase of additional generation capacity for overcoming the power generation shortage in North Cyprus. The idea is to determine the economically efficient reliability investment level, in which the social cost of not undertaking a reliability investment equals the marginal investment cost.

- **Decisions about where and when there should be a power cut off**

De Nooij et al. (2009) showed that blacking out those areas where social costs are lower could reduce the total loss up to 93% when compared to random rationing for the

Netherlands. Wenzel and Wolf (2014) conducted a study in Germany that determined that the gains may vary from 51% to 62%, depending on the hour of the day.

However, a priority rationing policy may not be fair to customers in areas where there is a low value of lost load¹ (VoLL), since these customers would suffer interruptions more often than others. One solution would be to financially compensate these customers by providing a rebate on their electricity bill, for example.

Define a rationing policy and calculating compensations for rationed consumers are some of the possible applications of the deficit cost. Nonetheless, there are some remaining questions for possible further research; for example, the homogeneity level within each area and the relation of social cost and outage duration may not be linear.

Praktiknjo (2016) suggests identifying the potential for demand-side management or even load shedding. He advocates that selective interruptions (that may be voluntary) to consumers with lower VoLL may be more cost-efficient than constructing generators that work for only a few hours a year.

Another article corroborates the idea of using quantitative results of unsupplied electricity marginal cost to develop optimum curtailment levels and priorities and plan curtailment strategies for electricity demand and supply (JU; YOO; KWAK, 2016).

- **Definition of energy consumption price**

Ozbaflı and Jenkins (2016) suggest that appropriately setting the energy price at peak hours may help to control the demand at those times and consequently avoid the outages at moments when the generation capacity meets the peak demand.

¹ VoLL pricing is setting the price of energy in the spot market to the VoLL price whenever the load has been shed. The market approach is to offer the value that consumers place on not being cut off (STOFT, 2002).

2.2 QUANTITATIVE EVALUATION OF POWER SUPPLY RELIABILITY – CONTEXT OF OUTAGE COST

Månsson et al. (2014) presented a comprehensive overview of commonly used methodologies for quantitative evaluations of supply security, one of which is the outage cost estimation by microeconomic approaches. The several aspects of energy supply security evaluation are divided into the following briefly listed subdisciplines.

- Macroeconomic methods: partial equilibrium models, impact assessments, and cost-benefit analyses that evaluate welfare loss from high or volatile prices;
- Industrial organization subdiscipline: dual diversity indices that evaluate, for example, exposure to market risk or specific risk;
- Financial theory: financial portfolios and real options theory that also measure exposure to market risk and specific risk and uncertainty and timing of investment decisions;
- Engineering methods: under subdisciplines, such as power and robustness of power systems (power system reliability assessments), to evaluate technical reliability; and operation studies (multicriteria analyses, analytic hierarchy process, fuzzy logic) to evaluate “holistic” supply chain security; and
- Microeconomic methods: surveys, production-function approach, market behavior, and case studies to evaluate the power outage cost, which is the focus of the present work.

2.3 OUTAGE COST ESTIMATION METHODOLOGIES

The microeconomic methods to evaluate the outage cost, cited in Section 2.2, are better explored in the present section. The deficit cost estimation methodologies observed during the bibliographic review and their cost drivers, which provide sensibilities to the outage cost, and the results of recent studies are presented.

An article written by Woo and Pupp (1992) gathered the most widely used methods in 16 other studies that estimated outage cost at that time. The article discusses customers that cannot choose their power reliability based on willingness to pay, as they may for other consumer goods, since electricity reliability depends on governmental regulatory aspects. In

the absence of a market that may provide consumers with energy service reliability choices, the willingness to pay (WTP) value becomes a measure of how much the lack of electricity costs. In other words, the WTP is often considered a proxy of the opportunity cost of unsupplied electricity or the electricity deficit cost.

The estimation approaches are grouped into what Woo and Pupp called the three techniques commonly employed to estimate outage costs. Sullivan and Keane (1995) also propose a similar methodology division, although the group names are somehow different. This section presents these three techniques by using both names encountered for each method, and an additional fourth methodology that does not seem to fit into the Woo and Pupp nor the Sullivan classifications.

The present section is divided according to the following methodology groups: Subsection 2.3.1 approaches the simple proxies / macro- and microeconomic models; Subsection 2.3.2, the market-based / revealed preferences methodology; and Subsection 2.3.3, the contingent valuation method / stated preferences. The fourth group is the case studies approach, presented in Subsection 2.3.4. Finally, Subsection 2.3.5 presents some additional understanding of the outage cost estimation methodologies classification, based on authors other than Woo and Pupp and Sullivan. The focus of Subsection 2.3.5 is the aspects that seem to be different from those used as a guideline for the division in section 2.3.

Table 1 presents the methodology classifications described in the following subsections, summarizing the essence of each and some approach examples.

Table 1 – Methodology classifications

	Simple proxies / macro- and microeconomic models	Market-based / revealed preferences	Contingent valuation method / stated preferences	Case studies
Description	Use secondary data as outage cost value.	Consumers reveal choices by behavior	Direct interviews and surveys of the customers	Infer outage cost by studying real events.
Approach examples	Average electricity tariff; backup power cost*; value of lost leisure (wage); value of lost production (may be estimated through input-output analysis or by the production- function approach)	Consumer surplus (which reveals consumer willingness to pay – WTP); cost-benefit analysis*; interruptible and curtailment rate options	Cost incurred (direct worth approach); direct questions about WTP and willingness to accept (WTA); Questionnaire with a set of options that combines WTP and reliability preferences.	Investigate information about an energy deficit that previously occurred to estimate losses during that period.

** For marked topics, some classification divergences were found among studies, as described in Subsection 2.3.5.*

Source: the author, based on Woo and Pupp (1992) and Sullivan and Keane (1995).

2.3.1 Simple proxies – macro- and microeconomic models

This Subsection is divided into two; 2.3.1.1 briefly presents some of the techniques that are considered simple proxy approaches, and Subsection 2.3.1.2 details an example of an input-output model application to measure the value of lost production due to an electricity outage.

2.3.1.1 Simple proxies – macro- and microeconomic models

Simple proxy techniques use secondary data to measure customer willingness to pay extra costs, such as average electricity tariff, cost of maintaining backup power, value of lost leisure or wage for estimating residential outage cost, and value of lost production (GDP per kWh consumed).

Some approaches were developed to calculate each of these proxies; for example, in the case of the proxy “value of lost production”, there is a production function approach and an input-output analysis approach; see Castro and Esteves (2016) for production-function and Praktiknjo (2016) for input-output analysis.

Although households do not usually produce goods or services that impact GDP, society is harmed by experiencing an outage at leisure moments. Some studies highlight this type of loss and consider leisure a household production (CASTRO; ESTEVES, 2016). From this viewpoint, the value of lost leisure is a proxy for the household outage cost. One estimation approach applied to this understanding consists of using the average wage value as the value of lost leisure. In this consideration, even under similar conditions of consumption per capita, it is possible to observe differences between household outage costs in different regions since there are differences in wage levels.

2.3.1.2 Value of lost production by an input-output model

This subsection presents an example of an input-output model applied to estimate the German outage cost (PRAKTIKNJO, 2016). Considering a delay of multiple years between publications, the German Federal Statistical Office publishes the yearly-based monetary input-output tables (MIOT) that provide information about the origin and usage of goods in 71 economic sectors. It also publishes the physical input-output tables (PIOT) containing the flow of goods not in monetary measures but in physical units. In this context, there are the energy input-output tables (EIOT) concerning the origin and usage of energy.

After adjusting values by the GDP-deflator index to compare the monetary cash flows of different sectors for different years, the Leontief input-output model is applied. The interlink of the economic sectors and eventual cascade effect can also be considered. In addition to the main consequence caused by the electricity sector reduction that is input to other economic sectors, the cascade event considers the secondary consequence from the reduction in inputs from other sectors that also underwent electricity reduction. The first model that considers cascade effects may be adequate for shorter interruptions, while the second model, which only considers the main reductions, might be more appropriate to estimate longer interruption costs.

One limitation of this method is that many factors that influence outage costs are not captured, such as duration, frequency, timing, and availability of backup batteries, among others.

2.3.2 Market-based – revealed preferences

The market-based approach uses preferences “revealed” by customers through their choices; in other words, observed customer behavior is used to infer the outage cost. Some of the analyses under this classification are the consumer surplus method or cost-benefit analysis, and the customer choice of interruptible and curtailment rate options analysis.

In his seminal book, Marshall (1890) cited the consumer surplus approach by explaining that consumers normally pay less than they are willing to pay to obtain satisfaction from their purchase. The excess of the price they would pay rather than go without the good is the so-called consumer surplus.

While Lacomme and Eto (2006) consider cost-benefit analysis a methodology to obtain the outage cost estimation, another article used this concept as part of a procedure that applies outage cost to determine the optimal power system capacity, instead of calculating the deficit cost itself (OZBAFLI; JENKINS, 2016).

Although the market-based approach is mentioned in some of the technical material about deficit cost estimation, a study that applies this technique was not encountered during the bibliographic review. The reason for the lack of practical application may be the absence of a real market that allows freely traded electricity system reliability or interruption options. To infer the value or to hypothetically question consumers about their preferences are respectively known as the proxy techniques in Subsection 2.3.1 and stated preferences in Subsection 2.3.3.

2.3.3 Contingent valuation method (CVM) – stated preferences

The contingent valuation method uses preferences stated by customers during interviews, in which individuals are asked to value hypothetical goods that are not priced in the market. Three techniques regarding this method are highlighted as follows (WOO; PUPP, 1992):

- i. To ask customers directly for the costs incurred in case of an outage (direct worth approach);

- ii. To ask customers about their willingness to pay (WTP) and/or willingness to accept (WTA) an increase (in case of WTP) or a decrease (in case of WTA) in service reliability (price proportional method);
- iii. To present customers with a set of hypothetical mutually exclusive service alternatives, one of which should be chosen. Each alternative indicates a combination of price and service reliability.

Some pending items regarding this approach include the status quo bias that influences answers and the method for validating the survey result by using market data in the absence of a specific market.

Corroborating the identified bias issue, Küfeoglu and Lehtonen (2015) used a mix of direct worth and price proportional methods to calculate the power interruptions economic impacts. One conclusion is that WTA is expected to be identical to WTP; however, there is a gap between these values that was determined by customer assessments. The fact that respondents are not necessarily fully aware of the true costs of power interruptions and the responses subjectivity is a critical factor regarding survey approaches.

2.3.4 Case studies

In 2014, a study reviewed historic worldwide blackout cases to obtain applicable conclusions for China (BO et al., 2015). Despite the impact estimation in terms of affected consumers and energy quantity, the monetary value costs are not calculated; the conclusions are mainly qualitative and include suggestions for actions.

2.3.5 Considerations about the methodology classifications

Despite the categories listed by Woo and Pupp (1992) used as guidelines to present the methodologies in this dissertation, some differences can be observed regarding the methodology classification used in other studies. For example, while Woo and Pupp classify the cost of maintaining backup power as a simple proxy, Beenstock (1991) states that it reveals consumer preference, which seems more like the description of Woo and Pupp's market-based approach category.

Another example of a divergence in methodology classification is the chain of functions described by Grosfeld-nir and Tishler (2016), which translates the outage cost as the damage incurred during a random sequence of outages. He called this approach “market-based”, although it seems more like a simple proxy based on the Woo and Pupp descriptions. The variables considered were production, as a function of electricity, and other priced inputs to production, other than direct damages (for example, inputs lost and labor used due to power outage), and profit loss due to a lower level of production. The outage time and length were both considered random.

2.4 COST DRIVERS

Many studies ascertain that outage cost is not the same in all occasions, yet a slight change in some assumptions can considerably alter the resulting cost. This section explores the conclusions of some studies concerning the drivers that may lead to differences in outage cost estimates. Subsection 2.4.1 presents the duration and frequency of the outage event as one of those factors, and Subsection 2.4.2, the time when the outage occurs. Subsection 2.4.3 presents the region issue, Subsection 2.4.4 and 2.4.5, the customer type and vulnerability, respectively. Finally, Subsection 2.4.6 introduces the prior notification issue, and Subsection 0 gathers other drivers not cited in previous items.

2.4.1 Event reliability – duration and frequency

Lacommare and Eto (2006), in their study of the United States (U.S.) area, identified that more frequent momentary power interruptions cause a greater impact on the total cost than do less frequent sustained interruptions; momentary interruptions contributed to two-thirds of the overall annual U.S. outage cost.

Other references also consider event duration and frequency to be important to estimate electricity reliability costs (ETO et al., 2001; KÜFEOĞLU; LEHTONEN, 2015; OZBAFLI; JENKINS, 2016).

2.4.2 Reliability event timing

Many studies tested the differences among timing of event occurrences. Some tests and their respective references are listed below:

- Afternoon versus night:
 - Lacommaré and Eto (2006) studied summer weekdays; the afternoon showed results that were 4.5 times greater than the night;
 - In Portugal, the 8 p.m. outage causes the most severe damage to households, while in the service sector, the outage in the morning, at approximately 10 a.m., does (CASTRO; ESTEVES, 2016).
- Season of the year:
 - The season of the year is viewed by Eto et al. (2001) as an important factor to the electricity reliability costs;
 - Castro and Esteves (2016) determined that outages occurring in winter incur higher costs than in summer due to the intensive use of electrical heating in Portugal.
- Weekday versus weekend:
 - Eto et al. (2001) state that the outage costs depend on customer behavior and production schedules;
 - Castro and Esteves (2016) verified that higher costs were incurred on weekdays than on weekends.

2.4.3 Region

Lacommaré and Eto (2006) concluded that the commercial and industrial population density results in different deficit costs, since the cost is proportional to these types of client distributions. This conclusion is similar to that by Nooij et al. (2007) in a study that verifies that the manufacturing sector presents a lower VoLL, while for the construction sector, households and the government have higher values.

2.4.4 Customer type

Lacommare and Eto (2006) conclude that the commercial and industrial sectors account for most of the outage cost, whereas the residential sector contribution to the total is minor. Castro and Esteves (2016), on the other hand, determine that there is a low VoLL for manufacturing industries and a similar and intermediate VoLL for the household and services sectors.

Praktiknjo (2016) published a study in which nonresidential consumers are separated into 51 economic sectors. Other studies also considered specific customer types to estimate interruption costs (KÜFEOĞLU; LEHTONEN, 2015; JU et al., 2016).

2.4.5 Customer vulnerability

Lacommare and Eto (2006) used a formula to estimate the interruption costs by applying the bottom-up approach, which is further explained in Subsection 2.5.1. One of the formula variables suggests that customer vulnerability may influence the outage cost. The technologies and measures to reduce their vulnerability include backup or standby generators and energy-storage technologies, such as batteries and flywheels.

Beenstock (1991) also explores the backup generators issue and consumer exposure to risks.

2.4.6 Prior notification

Nooij et al. (2007) did not consider prior notification in his study because at that time the Netherlands did not adopt this practice. In turn, Ozbaflı and Jenkins (2016) reported a large loss of utility if there is no prior notification. Küfeoğlu and Lehtonen (2015) considered prior notification as an input to produce a sensitivity analysis.

2.4.7 Other drivers

Some studies present cost drivers that are not recurrent in articles, which suggests that there may be many possible costs drivers that can significantly interfere with the result. Some of the observed nonrecurrent cost drivers are listed below (OZBAFLI; JENKINS, 2016).

- Younger respondents tend to suffer a larger loss of utility than older respondents do, maybe due to the lack of experience in coping with such inconveniences;
- People who live in apartments have a smaller loss of utility than those who live in detached houses. This might be explained by the better opportunity to share items used to mitigate power outages.

2.5 OTHER ASPECTS OF OUTAGE COST ESTIMATION

Other approaches for deficit cost estimation, in addition to those aforementioned, are explored in the following subsections. Subsections 2.5.1 and 2.5.2 show possible ways to solve the cost composition by sector, where the estimated value is calculated from a wider view and divided into smaller parts (top-down approach), or the opposite, that is, detailed research information composing a broader view (bottom-up approach).

Furthermore, an uncommon approach in Subsection 2.5.3 considers insurance valuation contents applied to the electricity deficit issue.

2.5.1 Bottom-up approach

Some studies recommend the bottom-up approach for outage cost estimation (ETO et al., 2001). The bottom-up estimate supports subanalyses for specific events, regions, or market sectors. Moreover, it is well suited for the future integration of information from different sources and perspectives, in addition to facilitating the integration of new information as it becomes available. Finally, this type of approach permits more structured data to assess uncertainty, prioritizes incremental data collection, and therefore improves credibility providing a foundation for qualifying the limitations for future analysis.

An example of the applied bottom-up approach is the Lacomme and Eto (2006) study, which estimates and basically sums the results for all types of regions, customer

classes, and events by multiplying the (i) number of customers; (ii) cost; (iii) frequency of the reliability event; and (iv) vulnerability of the customers, which is a fraction between 0 and 1. The simplicity of the formula belies the complexities involved in estimating each of the parameters in the equation.

2.5.2 Top-down approach

An example of a top-down model is the use of input-output tables to estimate the opportunity costs incurred by the sectors during a power outage (PRAKTIKNJO, 2016).

2.5.3 Insurance approach

Eto et al. (2001) recommend collecting information on customer spending on insurance and risk management efforts for insights on how insurers “value” electricity reliability. There are self-insurers that consider, for example, the expenditure on technological equipment for energy efficiency as an enhancement of electricity reliability. There is commercial insurance for business interruptions, data losses, property losses, and machinery breakdown, among other items. Self-insurance and commercial insurance each represent half of the 2001 insurance market, despite self-insurance trends of faster growth.

Ideally, premiums paid for insurance could be taken as a proxy for willingness to pay values for avoiding power disruptions. However, it is not possible to isolate the portion of premiums attributed to coverage related to power outages. In addition, not all citizens and businesses carry insurance, and not all insurance includes electricity interruptions. Payable losses can be capped, and in many cases, governmental entities assume part of the cost.

Beenstock (1991) explores the idea that expenditure on generators is analogous to the insurance premium.

2.6 OUTAGE COST VALUE – STUDY RESULTS

This section shows that studies concerning deficit cost are not homogeneous. Even using the same approach, for example, surveys of consumers, the methodologies observed are very diverse, as well as the results in terms of monetary cost and format. As seen in Table 2,

the unit measures for the cost are the monetary unit per kWh, year, 1 hour, 12 hours, month, and others. Even for the same study approach in the same country or region, the sensitivity analysis shows a wide cost range; it may vary by 4, 10, or almost 24 times or even more depending on the assumption used to measure the deficit cost. For example, Ozbaflı and Jenkins (2016) show the deficit cost in North Cyprus is almost 4 times higher depending on whether it considers the summer or the winter period.

Lacommare and Eto (2006) reviewed the subject to better understand the impacts of the massive electric power blackout in the northeastern US and Canada on August 14-15, 2003. Their conclusion shows the fragility in estimating the variables that may be used in outage cost calculations and the high sensitivity of the results, as seen in Table 2 – Results, compared with those of the results in other studies. Other relevant sensitivity analyses include changing assumptions about the time of events, which demonstrates the importance of using time-representative outage costs to calculate total costs.

Not all studies focus exclusively on outage cost estimation. Some of them have different conclusions. For example, Ozbaflı and Jenkins (2016) note that upgrading the physical system to increase its capacity is not the only way to enhance reliability or to prevent a deficit. During their survey, 87% of the consumers interviewed considered the price of their electricity high or very high. This means that they would not be willing to pay more for an improvement in the service. However, a reliability enhancement would be possible for a system with peak and off-peak pricing, once the consumption patterns respond to it.

Table 2 summarizes some of the studies reviewed during this bibliographic review. In addition to the estimated outage cost value, Table 2 presents observations highlighting the sensitivity analysis or other relevant aspects.

Table 2 – Results of the studies

Publication	Place	Methodology	Outage Cost	Other Observations
Lacommare and Eto (2006)	U.S.	Simple proxies	\$ 79 billion / year	Sensitivity analysis: \$ 22 to \$ 135 billion
Nooij et al. (2007)	Netherlands	Production- function	€ 159 million / hour (weekday, daytime)	-
Castro and Esteves (2016)	Portugal	Production- function	€ 5.12 / kWh	Differences among sectors: € 1.25 / kWh (manufacturing) to € 15.52 / kWh (construction and public works)
Reichl et al. (2013)	Austria	CVM for household and value-added production for nonhousehold (top- down method)	For a 12-hour summer power outage: Households: € 28.1 MM Nonhouseholds: € 449.7 MM	-
Ozbaflı and Jenkins (2016)	North Cyprus	CVM, WTP, choice experiment	Summer: 5.66 USD per month Winter: 21.97 USD per month	Only households; zero outage.
(Praktiknjo 2016)	Germany	Proxy: input-output model	Sector (EUR / kWh) Primary: 3.53 Secondary: 1.96 Tertiary: 13.23	Considering interlinkages of the sectors (EUR / kWh): 5.46 (primary); 3.33 (secondary); and 17.32 (tertiary).
Küfeoğlu and Lehtonen (2015)	Finland	Surveys: direct approach, WTP, WTA combined with the macroeconomic model	Households: from 3.6 to 36.36 € / kW depending on duration and estimation method	Only households, vacation houses and farm houses
Ju et al. (2016)	Korea	Proxy: input-output model	From 147 to 5,891 KRW / kWh	Depending on the economic sector, percentage and final demand.

Source: data compiled by the author

2.7 POSSIBILITIES FOR IMPROVEMENT

This section presents further steps that may improve outage cost estimates, as depicted by the studies analyzed. First, some materials consider the lack of detailed information as a relevant issue that harms estimations (ETO et al., 2001; LACOMMARE; ETO, 2006). Other reported items that could be enhanced are listed below.

- Detailed information on reliability events, such as duration, frequency, region (LACOMMARE; ETO, 2006);
- Detailed information on customers, such as type and backup generation capacity (LACOMMARE; ETO, 2006);
- The use of meta-analysis to improve confidence in synthesizing and extrapolating the existing database (ETO et al., 2001);
- In the case of using the input-output method, a possible improvement would be to apply other methods for estimating VoLL to refine a small limited number of sectors with economic potential identified by the first method (PRAKTIKNJO, 2016).

2.8 THE ELECTRICITY DEFICIT COST IN BRAZIL

The major causes of the electricity deficit in Brazil are derived from adverse hydrologic conditions, since the electricity matrix composition in Brazil is mainly hydroelectric. This kind of deficit is not solved in hours but in days, weeks, or even months. Structural causes require special dedication and creativity from the system operator to find immediate solutions to alleviate the impact on society.

In countries where thermoelectric energy is predominant in the electricity matrix, the electricity deficit occurs mostly due to the lack of thermal fuels or operational problems in certain power plants or transmission and distribution lines. This is usually solved in a few hours by replacing the energy supplier or ordering more fuel in the case of lacking fuel or by providing maintenance or replacing the damaged equipment or power lines.

Outage cost estimations throughout the world are commonly based on surveys that focus on stated and revealed preferences, measuring consumer losses during a relatively short period. Nevertheless, Brazil has adopted the simple proxy technique by considering the value

of lost production due to the lack of electricity as equal to the deficit cost. The Brazilian option seems to be more appropriate to measure structural deficit impacts.

Subsection 2.8.1 describes the practical application of deficit cost in Brazil, and Subsection 2.8.2 presents a related facts timeline. Finally, Subsection 2.8.3 summarizes the public hearings and the Brazilian studies analyzed for this bibliographic review.

2.8.1 Practical application of deficit cost in Brazil

The supply chain risk management best practices state that to address the fragility and risks of undelivered supplies, a company may define a tolerance to each undesirable event. For the undesirable event that may be out of the stipulated tolerance, the recommendation is to evaluate appropriate risk mitigation mechanisms and to develop a probability analysis, in addition to the consequences valuation before and after evaluating the risk mitigation mechanisms (SUPPLY CHAIN RISK LEADERSHIP COUNCIL, 2011).

This supply risk evaluating is similarly needed for the electricity power as an input; it is important to calculate the possible loss that an electricity deficit may cause for the country, as well as the occurrence probability. The possible damage valuation is called the “deficit cost” and may be measured in R\$ / MWh not supplied (monetary value per unitary energy consumption measure).

Just as recommended by the supply chain risk management best practices, decisions involving the Brazilian electricity sector are made aiming to minimize the deficit risks until, at least, an acceptable tolerance is achieved (KELMAN et al., 2001). The Brazilian stipulated tolerance is 5% of the deficit risk; in practical terms, at most 5% of the 2,000 scenarios simulated with the electricity system operation simulation official software can contain deficit possibilities other than zero.

The main decisions made based on that number include power plant dispatches by ONS and the electricity system expansion strategy. The criterion is an input to the short-market energy price formation. The policy and criteria for that calculation is currently determined by CNPE resolution n. 7 (2016).

D’Araujo (2004) explains the application of deficit cost to system expansion strategies. In Figure 5, the continuous curved line represents the energy cost without

evaluating any power plant expansion. This price is called the operation marginal cost (CMO – Brazilian acronym) and represents the cost of the next existing MWh to be generated. The continuous straight line is the expansion marginal cost (CME – Brazilian acronym), that is, how much the next MWh to be created in the system is, instead of dispatching an existing power plant. It evaluates the expansion of the national power plant park.

The level at which CME equals CMO determines the system critical load. From this point forward, it is worthwhile to expand the system instead of dispatching existing power plants.

The main cost driver of CMO is the fuel price; the greater the demand is, the more expensive the fuel. Furthermore, the need for rationing is higher if the installed park usage is near its full capacity. At that point, a policy worth considering is to discourage consumption by setting a higher CMO. That can be done by setting a higher deficit cost, since the deficit cost is an input to the CMO calculation. If the deficit cost increases, the CMO for the same load level also does.

The dotted curved line in Figure 5 evaluates a higher deficit cost than the continuous line. At the same load level, it is displaced to the left, leading to a higher CMO than the continuous line, which evaluates a lower deficit cost.

Figure 5 - Energy cost versus system load.

Source: Adapted from D'Araujo (2004).

Based on this concept, the two ways to consider deficit cost calculations are as explicit and implicit (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2001b). CNPE (2004)

resolution n. 1 determined that the deficit risk should be lower than 5% in each submarket, and CNPE (2008) resolution n. 9 provided the implicit methodology to calculate the CMO that equals CME, respecting this 5% acceptable risk.

The deficit cost parameter is input to the calculation of the guaranteed power of new generators, in addition to the plan for energy supply expansion. Nevertheless, the implicit calculation does not adequately reflect the impact of energy scarcity on society. In turn, the explicit estimation of the deficit cost includes balancing the service reliability and the production cost, providing an attractive return to stakeholders, a fair tariff to consumers and a reliable service (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2001b).

2.8.2 Deficit cost estimation timeline in Brazil

The deficit cost estimation has been debated in Brazil since 1985. Independent of the proposed methodology, the basic assumption has been the existence of a correlation between GDP evolution and electricity consumption. For that reason, a representative valuation of the importance of electricity to society, depicted by the deficit cost, is the impact caused by the electricity sector on the GDP (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2003a, 2003b).

Table 3 summarizes the history of the approaches used by the Brazilian official entity to understand or estimate the deficit cost. In 1988, the input-output table was used to calculate the Brazilian deficit cost, and that result is the same as that used so far, including a few updates, such as the GDP composition, foreign exchange rate and price index. The adopted price index is the general price index – domestic availability (IGP-DI – Brazilian acronym) that was developed and published by the Getulio Vargas Foundation and is extensively used in Brazil.

Table 3 – History of the electricity deficit cost approaches in Brazil**(to continue)**

Year	Description
1985 to 1988	Studies were conducted to establish the electricity deficit cost by using the input-output approach. The impact on the GDP of a unitary electricity power input reduction was evaluated for several economic sectors.
1988	The deficit cost curve was divided into levels, and the 1975 input-output table was used, which was the most recent table published at that time. ²
1997	The values calculated in 1988 were updated to 1996 values based on the electricity energy share in the GDP composition. This procedure was used in the explicit deficit cost project scope (CEDEF – Brazilian acronym) made by the Energy Planning Department (DPE – Brazilian acronym), a company primarily owned by the Brazilian government called the Brazilian Electricity Center (Eletrobrás) and the Electricity Energy Research Center (CEPEL – Brazilian acronym).
2001 (apr)	ANEEL promoted public hearing n. 2 to obtain information aiming to establish a deficit cost calculation methodology. The proposed procedure implied using an elasticity factor to correlate GDP and energy consumption. The methodology was developed by CEPEL and is detailed below. However, the public hearing process was not concluded at that time because a government committee to specifically assist the GCE was created. The provisional presidential decree n. 2.198-4 of 2001 removed some of the ANEEL attributes, including those related to the public hearing n. 2 issues.
2001	CEPEL published a study that applied linear regression to calculate the GDP and energy consumption elasticity. <i>Box-Jenkins</i> techniques were applied to temporal GDP and energy consumption series analyses ³ . The deficit cost calculation base year was 1998, and the results were updated to 2000 by the IGP-DI. Nevertheless, the methodology was not implemented. It was part of public hearing n. 2 already mentioned in this table.

² Subsection 2.8.3.2.1 presents more information on this methodology.³ Subsection 2.8.3.1.1 presents more information on this methodology.

(continued)

Year	Description
2002 (jan)	By using foreign exchange values (1 US\$ = R\$ 2.50), the 1997 curve was expressed in US\$/MWh, updated to R\$/MWh and published in resolution GCE n. 109/2002. This resolution was valid until December 31, 2002, at which date ANEEL should establish a new deficit cost calculation methodology.
2003 (nov)	ANEEL opened public hearing n. 46 to obtain information to establish the deficit cost curve update procedures, among other issues.
2003 (dec)	ANEEL resolution n. 682/2003 determined that the deficit cost curve published by GCE resolution n. 109/2002 should be updated by the IGP-DI to be considered in 2004. This resolution was a result of public hearing n. 46. The same resolution also stated that together, ANEEL, CCEE, which in 2003 was called the Electricity Wholesaler Market (MAE – Brazilian acronym), and ONS, would establish a new method to determine the electricity energy deficit cost. Competent institutions under the coordination of these entities should develop that method.
2004 to 2015	ANEEL published one resolution per year defining the deficit curve cost to be used the following year.
2014 (sep)	ANEEL published public call n. 002/2008 to promote a strategic research and development (R&D) project to define a deficit cost function construction methodology. The initial time frame to complete the project was 18 months, yet no result has been presented to date.

Source: information summarized by the author.

Subsection 2.8.3.2.1 provides further comments about the deficit cost estimation developed in 1988. After this first 1998 estimation, public hearing n. 2 was promoted by ANEEL (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2001b). At that time, the methodology used was an implicit calculation, which did not reflect the deficit impact on society or on the national economy. The proposal was to use an exogenous value as an input parameter to the computational system, making it possible to count on a more realistic price signal, as it would represent the economic loss due to the electricity deficit.

As of 2001, hydroelectricity has contributed to the majority of the Brazilian power generation, and reservoirs were very important to regularize the seasonal river flow and

guarantee a long-term electricity supply. Due to hydrological uncertainties, the power system operation is based on computational models, especially the Newave software, which optimizes the operational costs by determining strategies over several simulated scenarios of possible hydrologic conditions. The total operational cost for a given scenario consists of the sum of operational costs and the eventual deficit costs.

First, the 5% deficit tolerance was stipulated, and the implicit deficit cost was calculated. The technical note lists items influenced by the deficit cost including the short-term market liquidation of unbalanced energy consumption/selling or generation/buying, and the secured energy and power calculation assigned to the hydroelectric power plants that are part of the SIN.

The newly proposed methodology was developed by CEPEL and included in Annex I of the public hearing body of documents. The methodology proposed and the contributions received by the ANEEL public hearing n. 2 are explained in subsection 2.8.3.1.1.

GCE resolution n. 9 (2002) defined the deficit cost curve as a four-level function that is measured in R\$/MWh.

Two years after ANEEL public hearing n. 2, ANEEL public hearing n. 46 occurred in 2003, which despite a delay, aimed to meet GCE resolution n. 109 (2002). It determined that the cost deficit methodology should be defined until December 31, 2002 (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2003a, 2003b).

Technical notes n. 41 and n. 118 (2003), part of the public hearing body of documents, state the need to extend the period of studies to define a new estimation methodology. For that reason, a reference term to provide the selection of competent entities had to be elaborated. In addition to the competent entity definition process, the technical notes refer to the ONS concern regarding the current value update to provide a better price signal and, consequently, energy resources optimization in the power system operation programming.

For this, the technical notes list a series of simulations altering the deficit marginal cost input to observe the output CMO for each submarket and the total operational cost. The alternatives considered, which were each composed of the simulated scenario deficit values, were the updated values by the following inflation index: IGP-DI, IGP-M, IPCA, and the updated exchange rate.

The results showed a very low variation in operational costs among the simulated scenarios. No impediment was detected for the use of the monetary update of the deficit cost curve. The suggestion was to use the IGP-DI calculated by the Getúlio Vargas Foundation (FGV), since it is the index used by the Brazilian Central Bank as the implicit GDP deflator indicator.

As a result of public hearing n. 46, resolution n. 682 was published by ANEEL in 2003, determining that the deficit cost curve would be updated by the IGP-DI variation beginning in November 2002 for a period of 12 months. Moreover, the resolution determined that if necessary, a new methodology could be developed by a competent institution and coordinated by a task force composed of ANEEL, MAE (currently CCEE) and ONS.

Since 2004, ANEEL publishes a yearly resolution updating the deficit cost curve values. Until 2016, the deficit cost curve in Brazil was given at four levels, calculated by ordering the Brazilian productive sectors by their marginal cost that represents the GDP loss due to the electricity restriction. Those productive sectors were then divided into four clusters, each corresponding to a deficit cost level. The deficit cost of each level represents the average deficit marginal cost of the clustered productive sectors, weighted by their restricted amount when considering a production reduction of 30% (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2003a).

CNPE resolution n. 7 (2016) altered the deficit cost curve parameter to a single level calculated by the methodology presented in EPE technical note n. EPE-DEE-RE-014/2016-r0 (EMPRESA DE PESQUISA ENERGÉTICA; MINISTÉRIO DE MINAS E ENERGIA, 2016). Even before eliminating the adoption of four levels, EPE already calculated a single level value by applying this same methodology for expansion planning purposes. The methodology implies simulating several one-level deficit curve inputs in the Newave software and compare the resulting CMO with the result of the simulation that uses the four-level curve as an input. The purpose is to minimize the average and the standard deviation between the CMO output in both simulations, with four and one deficit levels. Beginning in 2018, the value calculated in 2017 is updated by IGP-DI.

Figure 6 presents the historical values of the deficit cost in Brazil since 2004, published by ANEEL. Each curve represents one of the four levels until 2016 (the 2017 four level values shown in the figure were published and then retracted in March 2017 to be

substituted by the single level value). A fifth series represents the single level cost published by EPE since 2006, except for the years 2007 and 2010 that are not available.

Figure 6 - Official deficit cost curve evolution - four levels and the single level.

Source: the author using ANEEL and EPE data.

2.8.3 Studies applied to Brazil

Two main approaches to calculate the Brazilian deficit were identified during the bibliographic review; one is the GDP and electricity consumption correlation, and the other, the input-output matrix analysis. This subsection translates this dissertation author's understanding of the steps presented by each proposal. The objective of detailing the approaches is to critically analyze each in Section 3, aiming to make the most of the ideas and to devote efforts to improve them.

The following subsections are separated by each main approach; that is, Subsection 2.8.3.1 is about two studies that use the GDP and the electricity consumption regression approach, and Subsection 2.8.3.2 presents two input-output matrix analysis studies. The topics within each subsection are separated according to each study analyzed.

2.8.3.1 Studies - GDP and electricity consumption correlation

This subsection describes the Brazilian studies based on the regression analysis model using GDP and electricity consumption. The methodology developed by CEPEL in 2001,

within the ambit of ANEEL public hearing n. 2, is summarized in Subsection 2.8.3.1.1. Subsection 2.8.3.1.2 presents the master's degree dissertation written by Loureiro in 2009, which replicates and updates the CEPEL study in addition to suggesting a new methodology.

2.8.3.1.1 CEPEL – 2001 (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2001b)

In 1999, ANEEL hired CEPEL to review the Expansion Planning Committee Coordinator (CCPE – Brazilian acronym) methodology elaborated in 1988. In 2001, ANEEL promoted public hearing n. 2 to publish the CEPEL study, intending to obtain contributions from experts. The present subtopic condenses the methodology developed by CEPEL.

The total operational cost for hydrothermal systems results from the addition of the thermoelectric power plants operational costs and the eventual supply deficit total cost. The supply deficit total cost, in turn, is the total electricity deficit amount multiplied by the deficit marginal cost. The definition adopted for deficit marginal cost is the amount of the GDP lost due to 1 MWh of restriction. The deficit cost calculated by using the concept of the GDP elasticity related to electricity consumption is expressed in Equation 1.

$$DC = \frac{dy}{dw} = \varepsilon(y, w) * \frac{y_{ref}}{w_{ref}} \quad (1)$$

where

DC – deficit cost per MWh

y – gross domestic product (GDP)

w – total electricity consumption in MWh (TEC)

$\varepsilon(y, w)$ – elasticity of GDP and electricity consumption

y_{ref} – GDP in the study reference year

w_{ref} – total electricity consumption in the study reference year

The study database includes GDP and consumption data from 1990 to 1998. The governmental Market Study Technical Committee (CTEM – Brazilian acronym) mapped the electricity consumption data, while the adopted GDP was published by the IBGE. The first step is to convert the GDP historical data current values to constant values by applying a specific yearly GDP deflator called the implicit GDP deflator. The historical data value is converted to the real value by multiplying the GDP deflator of each year by the GDP inflator

of its previous year. Equation 2 illustrates the example of a GDP value in 1990 current values updated to 1998 constant values:

(2)

GDP_{1990} in 1998

$$= GDP_{1990} \text{current prices} * (1 + ID_{1991}/100) * (1 + ID_{1992}/100) * (1 + ID_{1993}/100) * (1 + ID_{1994}/100) * (1 + ID_{1995}/100) * (1 + ID_{1996}/100) * (1 + ID_{1997}/100) * (1 + ID_{1998}/100)$$

where

$ID_{[year]}$ is the GDP implicit deflator.

At the time of the CEPEL study, the total electricity consumption was the sum of the following consumer categories: firm consumption, special tariffs and self-production. The firm consumption data was divided into industry and other consumer categories. For the industry firm consumption data, 95% were provided by distribution companies and separated into economic sectors, and the other 5% were estimated using the other 95% for which direct information was obtained. The consumption data for the other consumer categories were copied from the Market Integrated System Report (SIN – Brazilian acronym) published by Eletrobrás.

The special tariffs consumption data represented 2% of the total. These data were also provided by the distribution companies, and the 30% that was not provided was estimated proportionally based on the provided data. Self-production represented 6% of the total consumption. The values of the national energy balance (BEN – Brazilian acronym) published by the National Department of Energy were adopted as a baseline.

The logarithms of the GDP, the consumption per year, and the difference between the years in sequence are calculated, as shown by Equation 3.

$$\Delta \log y_t = \varepsilon(y, w) \Delta \log w_t + e_t \quad (3)$$

where

$$\Delta \log y_t = \log y_t - \log y_{t-1}$$

$$\Delta \log w_t = \log w_t - \log w_{t-1}$$

e_t - random noise

Using a regression model adjusted by least squares over the variations of $\Delta \log y_t$ and $\Delta \log w_t$, elasticity $\varepsilon(y, w)$ was obtained. The resulting elasticity can then be applied to Equation 1 to obtain the deficit marginal cost that, updated to October 2000, was R\$ 2,328/MWh.

The deficit cost result was updated from 1998 to October 2012 when the public hearing report was published by dividing the October 2012 IGP-DI index by the 1998 average index. The quotient was multiplied by the 1998 deficit cost to obtain the deficit cost on October 2012.

This public hearing methodology suggestion received unfavorable reviews that punctuated the inadequacy of having the same marginal deficit cost for small and large deficits (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2001a). In addition, the GDP has many former drivers, and the proposed methodology does not capture the electricity deficit effect over various economic sectors or different Brazilian regions since it considers the aggregated historical series. The standard deviation calculated in the study is approximately 1/4 of the total value, revealing a large data inaccuracy. At that time, ANEEL technical note n. 118 (2003), published as part of the body of documents of public hearing n. 46 conducted in the same year, determined that the length of the studied historical data series was too short to provide a reliable result.

One reviewer suggested periodic revision every 5 years. Others suggested that the impacts observed in 2001, which was the Brazil electricity rationing year, could be used to parameterize the Brazilian deficit value. Some of the reviewers disagreed on changing the deficit cost parameter at that time of delicate rationing and advocated that the market should have an adaptation period to the economic signal that would result in system expansion once the deficit value alters short term prices, which may greatly affect the cash flow for market agents.

2.8.3.1.2 Loureiro – 2009 (LOUREIRO, 2009)

In 2009, Paulo Loureiro updated the CEPEL study using the same methodology applied to the period between 1995 and 2007 and proposed a new calculation methodology. The GDP database used was published by the Applied Economic Research Institute (IPEA –

Brazilian acronym), and it had constant values for the 2007 base year. The electricity consumption database was published by EPE.

Using the same CEPEL formulas presented in Subsection 2.8.3.1.1, the GDP and consumption log differences for each consecutive year were calculated and the linear regression was adjusted by the least squares method. The result for 2007 was $CD_{2007} = 3,084$ R\$ / MWh.

In addition to this update exercise, a new estimation methodology was proposed. One main difference between the CEPEL study and Loureiro's new methodology proposal is that the latter uses monthly data instead of annual data. The first step aimed to demonstrate the relevance of the correlation between the two analyzed variables of GDP and consumption. A linear regression was applied directly to the data series, without applying the log calculation first. The determination coefficient (R^2) obtained by this procedure was 0.9.

Another correlation analysis was performed with the following steps: the monthly variation of each variable (GDP and consumption) was considered, excluding the data that corresponded to periods in which the variation sign (positive or negative) of one variable was different from the other. Also eliminated from the analysis were those points at which both variations were negative. The values left were those in the first quadrant of the graphic plot over which a linear function was suggested to better fit the behavior of the remaining data, in this case, a logarithmic function.

The estimation calculation was based on the following two different approaches: the risk analysis approach and the level treatment approach. Both were simulated and compared by Loureiro.

In the risk analysis approach, a computational software, developed by CEPEL, simulating individualized hydropower plants in interconnected systems (SUISHI-O – Brazilian acronym) was used to calculate the maximum electricity value expected to be supplied without a deficit; a value that Loureiro called “firm” energy. The hydrological history series from 1931 to 2006 were inputs to SUISHI-O, associated with the hydropower park expected in 2012, the year that represents the analysis horizon. For the hydropower capacity result, the thermopower plant capacity expected was summed, in addition to that of all other small power plants, to result in the total system capacity in 2012.

The results of those 76 simulations (one per hydrological yearly series) made by SUISHI-O is shown in a histogram that indicates that the “firm” energy was the safest value for the power system, the value that was the lower capacity result from the 76 simulations.

The next steps used the standard deviation measure derived from this process. The “firm” energy, which was the lowest value among the simulations results, is used as the average of a supplied market perfect normal probability distribution curve. It means that values of supply and demand above this “firm” energy value are considered a deficit scenario. Some classical statistics formulas are then applied to obtain deficit probabilities associating magnitude (GWh) and cost (R\$/MWh). By doing this, it is assumed that half of the scenarios result in a deficit.

Equation 4 and Equation 5 present the Z-score and standard deviation formulas, respectively, both obtained from classic statistics books to better explain Loureiro’s logic (TRIOLA, 2012).

$$Z_i = \frac{x_i - \mu}{\sigma} \quad (4)$$

where

x_i - value for which the Z-score is being calculated

μ - average population value

σ - standard deviation (statistical concept explained in Equation 5)

$$\sigma = \sqrt{\sum \frac{(x_i - \mu)^2}{n}} \quad (5)$$

where

n - sample size

For Loureiro, μ would be the “firm” consumption, and x_i , the “permitted” consumption as deduced by applying Equation 6 to Equation 4. Those x_i values lower than μ indicate that there is no deficit, and consequently, the “permitted” consumption that corresponds to negative Z-scores result in a 0% deficit probability. Only the positive Z-scores were used to

calculate the deficit magnitudes (GWh) by using Equation 6. That calculation was repeated for each 1% probability interval.

The standard deviation obtained by the SUIISHI-O scenarios was multiplied by the corresponding Z-score that associates each probability area. Loureiro proposed Equation 6 is naturally associated with the classic Equation 4.

$$\text{"permitted" consumption} - \text{"firm" consumption} = \text{Deficit (D)} = Z * \sigma \quad (6)$$

The monetary impact (R\$) was estimated for each probabilistic possibility of the deficit occurrence by using the logarithmic function that correlates GDP and consumption. The results for the 2009 values were as follows: with a 5% deficit probability, the total deficit cost was R\$ 11.114 / MWh, equivalent to a deficit of 4.017 MWh; and with a 1% probability, 797 MWh, and a marginal deficit cost of R\$ 7,497 / MWh.

The deficit magnitude versus the monetary impact calculated for each percentage probability resulted in another logarithmic function derived to determine the marginal cost. The result was an equation of the GDP variation as a function of a unitary deficit (GWh). The 5% risk level was chosen; hence, the associated total deficit was used in the derived equation.

The second approach was the deficit level approach, in which the deficit magnitude is the focus. The energy market was divided by 100, or 1% intervals. By using the same logarithmic function correlating GDP and electricity consumption, each 1% load reduction was evaluated in R\$. After determining the level intervals of 0-5%, 5-10%, 10-20%, and above 20%, an average deficit value for each level was calculated by using the extreme points of each level to consider the cost variation divided by the energy amount variation. The result for the 0-5% level was R\$ 4,932.32 / MWh. In addition, a weighted average to obtain only one level deficit cost was calculated and resulted in R\$ 6,157 / MWh.

Finally, by using the computational model Newave with each of the deficit cost results as inputs, the system operational marginal cost and the system total operational cost were observed to be higher as the deficit marginal cost was higher due to the direct influence of the deficit marginal cost on the operational cost. In addition, the deficit risk and the unsupplied energy amount was lower as the deficit marginal cost increased due to a financially optimized

solution that simulated the use of more resources instead of allowing costly deficit occurrences.

2.8.3.2 *Studies – input-output analysis to estimate the deficit cost*

This subsection summarizes two Brazilian studies that use the input-output analysis, beginning with the Final Report published in 1988 in Subsection 2.8.3.2.1, and followed by a study that was developed by Vasconcelos and Carpio (2015) in Subsection 2.8.3.2.2.

2.8.3.2.1 Final Report of the Deficit Cost Study Commission (GRUPO COORDENADOR DO PLANEJAMENTO DOS SISTEMAS ELÉTRICOS, 1988)

The methodology applied in 1988 used the Leontief model as a starting point that measures the impact on the production of each economic sector as the final demand is altered.

There were two steps as follows: first, the GDP at social prices was calculated; second, the global electricity restriction cost was calculated, in other words, the deficit cost, which is the final objective. The deficit cost in this methodology is the variation of the GDP at social prices calculated in the first step due to a unitary electricity production variation.

All of the following calculations are expressed in monetary units. There are substeps to obtain the GDP at social prices. The GDP (also called the total added value) is given by the sum of the primary input values for all sectors, which are, in turn, obtained by multiplying the production for each sector by a primary input coefficient matrix. This matrix relates the primary inputs to the production for each sector.

Equation 7, further detailed in Equation 14 in Section 3.1, describes the total sectoral production calculated by the Leontief formula.

$$X = (I - A)^{-1} * D \quad (7)$$

where (matrix size in brackets when suitable)

X - gross sectoral production (n x 1)

A - intersectoral technical coefficients (n x n)

I - identity matrix (n x n)

D - final demand vector (n x 1)

n - number of productive economic sectors

Equation 8 describes how the social GDP is obtained. The Power System Planning Coordinator Group (GCPS – Brazilian acronym) methodology proposes an optimization system to calculate the vector S that is not studied in this thesis but suggested as future analysis work.

$$P = S * R * X \quad (8)$$

where

P - social prices GDP (value)

S - vector of market price conversion into social prices (1 x m)

R - matrix of primary input technical coefficients (m x n)

As stated before, the global electricity cost restriction is the difference in the social GDP caused by an electricity production variation. Since vector S in Equation 8 converts market prices into social prices and matrix R regards the primary input proportion of each sector production, in a given scenario both are constant. The single factor that interferes with the resultant social GDP is X, which represents the gross sectoral production. Therefore, an electricity production alteration implies a variation in the production of other economic activities and, consequently, social GDP.

To identify the sectoral production X variation due to the electricity sector variation, the elasticity concept is adopted; a sector production variation due to the electricity production variation may be obtained by multiplying an elasticity factor by the relation between the total analyzed sector production and the total electricity sector production. Equation 9 depicts the GDP variation applied in Equation 8.

$$\frac{dP}{dXe} = S * R * \frac{dX}{dXe} \quad (9)$$

Equation 10 applies the elasticity concept to Equation 9.

$$\frac{dP}{dXe} = S * R * EXXe * \frac{X}{Xe} \quad (10)$$

where

X_e - electricity production

$EXXe$ - matrix in which the main diagonal element corresponds to the productive sector elasticity due to the electricity sector (n x n)

Finally, since P and X_e are measured in monetary units, their variation division result is a dimensionless value. The electricity deficit cost for an energy unit is the result given by multiplying the dimensionless number obtained in Equation 10 by the energy unit price, which is the electricity tariff, as shown by Equation 11.

$$w = \frac{dP}{dXe} * T \quad (11)$$

where

w - electricity deficit cost

T - average electricity tariff

2.8.3.2.2 Vasconcelos, Sergio and Carpio, Lucio – I/O analysis (VASCONCELOS; CARPIO, 2015)

In 2015, Sergio Vasconcelos and Lucio Carpio published a study estimating the Brazil outage cost through a methodology that uses the input-output matrix as a database. In the analyzed article, electricity comprises one of the twelve productive sectors, while the GDP and imports comprise the primary inputs.

First, the technical coefficients of the productive sectors were calculated composing matrix A , as further described in Subsection 3.1.1.1, and then, a linear reduction considering the proportional distribution of the supply side is adopted, as demonstrated in theoretical Table 4 transcribed from the article.

Table 4 – Input-output table with four sectors: application of multipliers

Input–Output table with multipliers						
Sectors	A_1	A_2	A_3	A_4	Final demand	Total outputs
A_1	R_1x_{11}	R_1x_{12}	R_1x_{13}	R_1x_{14}	R_1C_1	R_1X_1
A_2	R_2x_{21}	R_2x_{22}	R_2x_{23}	R_2x_{24}	R_2C_2	R_2X_2
A_3	R_3x_{31}	R_3x_{32}	R_3x_{33}	R_3x_{34}	R_3C_3	R_3X_3
A_4	R_4x_{41}	R_4x_{42}	R_4x_{43}	R_4x_{44}	R_4C_4	R_4X_4
Primary inputs	q_1B_1	q_2B_2	q_3B_3	q_4B_4		
Total inputs	R_1X_1	R_2X_2	R_3X_3	R_4X_4		

Source: Vasconcelos and Carpio (2015).

where

x_{ij} – flows among productive sectors i and j

X_j – total inputs of sector j

C_i – final demand of sector i

B_j – primary input of sector j

R_i – the multiplier effect of the productive sector i

q_j – the multiplier effect of the primary input of sector j

In addition to the technical coefficients a_{ij} , the article proposes a technical coefficient that translates the proportion of the primary input over the total production $b_j = B_j / X_j$. The next step is to adopt multipliers for Table 4 by replacing the total values of the inputs x_{ij} by the technical coefficients a_{ij} . Equation 12 summarizes the building process of the linear equations system used in the developed solution.

$$R = ((I - A)^{-1})^T * qb \quad (12)$$

where

b - primary input coefficient

A – technical coefficient matrix (translates the input of sector i to produce a monetary unit of sector j product or service)

3 METHODOLOGY

The present section has two objectives as follows: the first is to critically analyze the methodologies presented in Subsection 2.8.3 - *Studies applied to Brazil*; the other is to propose two new methodologies. Before that, there is a review on the input-output matrix subject in Section 3.1.

Section 3.2 aims to present this dissertation author's personal evaluation of the content introduced in Subsection 2.8.3, enlightened by the literature, especially in the statistics and in the econometrics areas.

Sections 3.3 and 3.4 detail the proposed calculation steps of two different approaches. In this chapter, the methodology is explained, and in Chapter 4, the results are detailed and analyzed. The first approach, presented in Section 3.3, employs the GDP and electricity consumption correlation, and the second approach, presented in Section 3.4, applies the input-output matrix analysis.

The present dissertation study makes use of knowledge accumulation, one of the scientific field requirements that means continuing a research line, instead of competing and proposing an infinite and endless succession of new theories (CALDAS, 2003). In practical terms, this means that those methodology proposals critically analyzed in Section 3.2 are used as a base for the reproduction, update and improvement of the methodologies proposed in Sections 3.3 and 3.4.

3.1 A REVIEW OF THE INPUT-OUTPUT MATRIX

This section presents a review of the input-output (I/O) matrix analysis content. Although the main source of the concepts described here is the book by Miller and Blair (2009), the Brazilian case is also considered for some explanation points based on the data published by the IBGE (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2017). In addition, the input-output matrices applied in the present study, developed by Guilhoto and Filho (2005; 2010), are also considered as an information base in the present subsection.

The input-output matrix presents an economic photograph of a certain region; in the case of the present work, the region is Brazil. The matrix shows the resources and use quantities of

each productive sector in relation to other sectors and to the final consumption, such as households, governmental and nongovernmental institutions, in addition to exports, gross fixed capital formation and stock variation. In addition to the supply to productive sectors presented in basic prices, there is a line containing the imports as well as the items composing market prices over production basic prices such as transport and trade margins, indirect taxes and import taxes. Finally, there is the added value, which is the sum of payments, direct taxes and gross operational surplus including land and capital payments. The added value is important in the present dissertation since its variation due to a shock caused by the electricity sector is the answer this study aims to find.

The matrix considers lines as inputs to the column items; for example, in Table 5, z_{ij} is the amount of sector i production consumed by sector j , and d_j is the parcel of the sector production destined to final consumption.

Table 5 – Input-output matrix framework

		Processing sectors			Exports	Final demand	Gross fixed capital formation	Stock variation	Total
		1	2	3					
Processing sectors	1	z_{11}	z_{12}	z_{13}	e_1	d_1	c_1	s_1	x_1
	2	z_{21}	z_{22}	z_{23}	e_2	d_2	c_2	s_2	x_2
	3	z_{31}	z_{32}	z_{33}	e_3	d_3	c_3	s_3	x_3
	Margins - transport /trade	m_1	m_2	m_3					
	Indirect taxes	it_1	it_2	it_3					
	Imports	i_1	i_2	i_3					
Value added	Payments	p_1	p_2	p_3	-				-
	Direct taxes	t_1	t_2	t_3					
	Gross operating surplus	g_1	g_2	g_3					
	Total	x_1	x_2	x_3	-				$\sum x_j$

Source: the author.

Subsection 3.1.1.1 presents the Leontief inverse matrix classic application to the I/O analysis, and subsection 3.1.1.2 presents the Ghosh inverse matrix application, which builds analysis alternatives over the Leontief theory. Additionally, for the input-output analysis bibliographic content, subsection 3.1.1.3 presents the information on the electricity data composition used in the Brazilian I/O matrix. Subsections 3.1.1.4 and 3.1.1.5 briefly present

topics on the hybrid matrix and closed models, respectively, despite not detailing them, since the final decision was not to apply them to the proposed I/O analysis methodology.

3.1.1.1 Leontief inverse – electricity supply variation impacting production

Professor Wassily Leontief received the Nobel Prize for Economic Science in 1973 due to the analytical framework he developed in the late 1930s known as input-output analysis, or interindustry analysis.

The z_{ij} items presented in Table 5 translate the production technology of each productive sector; in other words, they compose a Z matrix showing in monetary unity how much of sector i production is used as input to sector j production, also known as secondary or indirect demand. Note that the values of those transactions are measured in basic prices because using the consumer prices would obscure production relations, unduly mixing transport margins, trade margins and indirect taxes.

The input-output framework analyzes the amount of production variation necessary in each sector to meet a given final demand variation for each sector. In addition to the final demand itself, it also considers the secondary needs that each sector demands from others to produce each output unit. The following sequence of equations presented in Equation 13 and Equation 14 results in the Leontief inverse matrix, directly applied as a final exogenous demand multiplier, which results in the production necessary to supply the given demand.

The first step consists of knowing the supply amount for each sector that is necessary to produce one single monetary unit of a sector output. That quantity is determined by dividing each z_{ij} amount by the total production x_j . The resulting matrix is called the technical coefficient matrix (A).

$$A = \begin{bmatrix} \frac{z_{11}}{x_1} & \dots & \frac{z_{1j}}{x_j} \\ \vdots & \ddots & \vdots \\ \frac{z_{i1}}{x_1} & \dots & \frac{z_{ij}}{x_j} \end{bmatrix} = Z * \hat{x}^{-1} \quad (13)$$

$$a_{ij} = \frac{z_{ij}}{x_j}$$

where

$\hat{x}$ – diagonal matrix of vector x elements

z_{ij} – how much of sector j production is an input to sector i

A – technical coefficient matrix

Multiplying the technical coefficient matrix by an amount of production in monetary units results in the secondary demand to supply that amount of production. The sum of the secondary intersectoral demand and the primary exogenous final demand results in the total demand required from each economic sector. That is, to achieve a final demand of some product, the demanded sector consequently demands products from other sectors that are the inputs necessary to compose its own output. Equation 14 shows the total production composition, which is the final demand plus the intersectoral demand.

An algebraic manipulation sequence leads to the Leontief inverse matrix, which directly multiplies the final demand by the result of the total production amount.

$$\begin{aligned} x &= d + A * x \\ x - A * x &= d \\ (I - A) * x &= d \\ x &= (I - A)^{-1} * d \\ x &= L * d \end{aligned} \quad (14)$$

where

I – identity matrix

d – final demand vector

x – total production vector

L – Leontief inverse matrix

3.1.1.2 Ghosh inverse – GDP variation impacting production

In 1958, Ghosh presented an alternative input–output analysis that permits an added value shock instead of a final demand shock, while the desired result is still the total production variation per sector.

For that, instead of building the technical coefficients in matrix A, he used the allocation coefficients in matrix B. The single difference between both is that the total production in the denominator of matrix A elements is the demanding sector, while the supplying sector is in matrix B. Equation 15 indicates that the total production considered for each element denominator is the line total, instead of the column total as observed in matrix A, presented by Equation 13.

$$B = \begin{bmatrix} \frac{z_{11}}{x_1} & \dots & \frac{z_{1j}}{x_1} \\ \vdots & \ddots & \vdots \\ \frac{z_{i1}}{x_i} & \dots & \frac{z_{ij}}{x_i} \end{bmatrix} = \hat{x}^{-1} * Z \quad (15)$$

$$b_{ij} = \frac{z_{ij}}{x_i}$$

Analyzing the I/O columns in Table 5 deduces that the total national production of a determined sector x_j is the sum of the intersectoral demand of this sector plus its added value. The sequence in Equation 16 presents the steps to obtain the Ghosh inverse matrix. Note that for correct algebraic manipulation and reasoning, matrix B is transposed, resulting in matrix B' .

$$\begin{aligned}
x &= v + B' * x \\
x - B' * x &= v \\
(I - B') * x &= v \\
x &= (I - B')^{-1} * v \\
x &= G' * v
\end{aligned}
\tag{16}$$

where

$$G = (I - B)^{-1}$$

v – added value vector (items in addition to the intersectoral matrix).

Every item not included in matrix Z should be part of vector v . That implies giving a shock on values other than those included in matrix Z to determine the total national production reaction. Hence, vector v may be considered the exogenous data, useful to verify, for example, the impact of a labor strike on the economy of a region.

3.1.1.3 Electricity sector in the Brazilian I/O matrix

Methodology notes written by IBGE explain that the electricity, natural gas and other utilities sector data published in the Brazilian National Accounts Reports were obtained from specific electricity and gas sector institutions (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2000a, 2000b, 2010). Because the 2010 methodology notes do not detail electricity data composition, the 2000 specific methodology note n. 16 is used as a reference (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2000b).

The 2000 methodology note n. 16 explains that the electricity production data are obtained from the operational income declared on the balance sheet of the electricity companies, who have to provide ANEEL with their financial statements. That excludes independent or self-consumption producers. The understanding is that self-consumption producers do not contribute to the added value (GDP) since they do not commercialize electricity. The parcel sold, in turn, has its income considered as “other income” in the survey conducted by IBGE; hence, separately counting the energy income would result in a double counting of these receivables.

In addition, Itaipu, the major Brazilian electricity generator, is considered by converting the US dollar income to the Brazilian Real monetary unit and, since Itaipu is a binational company, the Paraguay parcel consumed by Brazil is considered as an import.

Electricity exports are despised, and intermediate consumption is obtained from the National Energy Balance (BEN – Brazilian acronym) report published by EPE, in which the electricity consumption is divided into residential and nonresidential. The latter is considered the intermediate consumption in the production matrix. The intra-consumption values are based on the energy bought by distribution companies to resale and other income statement information such as materials, third-party services and other expense rubrics.

Analyzing some reports published by the Brazilian Piped Gas Association (ABEGAS – Brazilian acronym) on their website, it is possible to identify that approximately 40% of the total gas is used to generate electricity, and nearly 40% is consumed by the industrial sector (ASSOCIAÇÃO BRASILEIRA DAS EMPRESAS DISTRIBUIDORAS DE GÁS CANALIZADO, 2012).

3.1.1.4 Hybrid I/O matrix

One of the first steps taken by the statistical institutes that publish economic national data to compose an I/O matrix is to convert all inputs and outputs from physical units to monetary units. Nevertheless, for some analyses, it may be interesting to work with the physical units instead of the monetary units. There are specific techniques applied to make use of this, and some of their uses include energy conservation problems and carbon emissions, among others.

3.1.1.5 Closed models

There is an understanding that an increase in the payments made to households by the productive sectors may influence the family consumption volume. The closed model approach consists of internalizing the families demand and payments received into the production system. In that frame, household and family payments are respectively inserted as an additional column and line to compose matrix Z. If a demand shock increases the production, it also increases the payments to households and, consequently, the power consumption by the

families. The consumption proportion between sectors is kept and the households sector provides feedback to the other productive sectors by generating a secondary demand.

3.2 ANALYSIS OF METHODOLOGIES PROPOSED TO CALCULATE THE BRAZILIAN DEFICIT COST

The present section aims to evaluate those studies described in subsection 2.8.3 - *Studies applied to Brazil*. An important comment to be made about this subsection is that in all the analyzed studies, a great development effort seems to have been invested, in addition to positive creativity to innovate this complex issue in the electricity sector. The intention of the present work is to humbly further the understanding of those carefully developed methodology steps to improve and to contribute to the maturity of the deficit cost calculation debate.

Those subsections are divided into the two main methodologies identified in the Brazilian bibliographic review as follows: the GDP and electricity consumption correlation in Subsection 3.2.1 and the input-output matrix analysis in Subsection 3.2.2.

3.2.1 GDP and electricity consumption correlation

Two Brazilian studies that calculated the deficit cost by correlating GDP and electricity consumption were taken into consideration in the development of this dissertation in Subsection 2.8.3.1. The present subsection raises questions about some of the steps or data considerations, enlightened by the knowledge of statistics and econometrics (GUJARATI; PORTER, 2011; TRIOLA, 2012; WOOLDRIDGE, 2016).

Loureiro's reproduction of the CEPEL regression model, besides the CEPEL methodology itself, is analyzed in subsections 3.2.1.1 to 3.2.1.3. Additionally, the new methodologies developed by Loureiro are analyzed in subsection 3.2.1.4.

To better organize the study analyses content, each of the following subsections addresses a specific data analysis topic as follows: Subsection 3.2.1.1 regards the data set size; 3.2.1.2, the linear regression form (log-log and level-log); 3.2.1.3 describes the interception coefficient; and 3.2.1.4 presents some other methodology-specific considerations.

3.2.1.1 *Data set size*

One main difference between the CEPEL prior study and Loureiro's reproduction is the interval of the data collection (GDP and electricity consumption); CEPEL used yearly data, while Loureiro used quarterly data. Each has some disadvantage; in the CEPEL case, there were only 8 years composing the database, which is a very small sample yield for reliable results.

Loureiro, on the other hand, used monthly data that populates the database in 13 years, which represents 156 GDP and consumption pairs to input. That seemed to be a great sample, had it not been for the need to remove three quadrants of the correlated data plot to fit them into a logarithmic curve regression, which does not accept negative x values. The sample decreased to 43 periods, which represented only 28% of the initial sample size, which do not seem to be representative.

One additional comment is that measuring the GDP variation is not a simple job; hence, maybe one month is too short of a period to provide sufficient accurate data to be considered reliable input data. Official GDP data in Brazil and the USA, for example, are published quarterly.

3.2.1.2 *Regression form*

Another difference between the CEPEL and Loureiro methodologies is that CEPEL uses logarithmic operations to estimate elasticity, while for Loureiro, the logarithm works as an equation model itself, without applying the elasticity concept. The logarithmic base is different when both methodologies are compared. CEPEL calculates the logarithm to base 10 of each input data and then calculates the differences between periods to obtain the values used in a linear regression model that results in a log-log regression form. Loureiro, instead, applies a regression of GDP over electricity consumption directly on monetary and consumption variation between each period. After testing some function curves over plotted data, a logarithmic curve seemed to fit best, thus obtaining a level-log model using a natural logarithm (base e).

In the case of the log-log model, to use log to base e is more common than to base 10, although in both bases the equation slope parameter is used as an elasticity coefficient, resulting in a nonlinear GDP variation.

The resulting equation by Loureiro, correlating GDP and electricity consumption, seems to be the less frequent elasticity analysis function form that is the level-log, since in this case the log was applied only to the consumption and not to the GDP. The level-log form is read as if 1% variation over the electricity consumption implies a variation in the GDP value equal to the angular coefficient divided by 100, as summarized in Table 6.

Table 6 – Functional logarithmic forms

Model	Dependent variable (GDP)	Independent variable (electricity consumption)	Angular coefficient (β_1) interpretation
Log-log	$\log(y)$	$\log(x)$	$\% \Delta y = \beta_1 \% \Delta x$
Level-log	Y	$\log(x)$	$\Delta y = (\beta_1/100) \% \Delta x$

Source: adapted from Wooldridge (2016).

3.2.1.3 *Interception coefficient*

CEPEL used regression through origin, which means eliminating the interception coefficient. That is not the usual practice, since the resulting angular coefficient in those cases may be biased. Moreover, the interception coefficient is not important in linear regression analysis, since the main objective of the linear regression is to obtain data variation behavior translated by the angular coefficient. Indeed, to use the interception in the CEPEL specific case results in a negative interception, albeit near zero. That would mean that the GDP variation would be less than zero in the absence of consumption variation, which does not seem to be a disposable idea, since the consumption stagnation might imply an economical reduction.

3.2.1.4 *Other considerations*

One additional consideration involves the methodology used by Loureiro to obtain the deficit magnitude associated with the occurrence probability. The understanding was that the lowest hydropower system capacity obtained by simulations in SUISHI-O was considered the

average consumption in a normal probability distribution curve that had the same standard deviation as those 76 simulated hydropower capacity data.

It seems that the consumption data have the same behavior as hydrology probabilities. Even if a fixed consumption is considered and the hydrology variation employs the same distribution data parameters, the average considered in the distribution was the lowest obtained in the simulations, therefore implying supply uncertainties in any other possibility. A standard deviation value probably should be referenced by the average of the simulation results, instead of the minimum value.

Using the minimum value as a base, all other results would be naturally greater than the base, and if lower values existed, they would imply a deficit risk. Additionally, the variable considered for electricity consumption might have its own distribution parameters that could be better analyzed, instead of simply considering its behavior equal to the hydrology behavior.

3.2.2 Input-output analysis

Enlightened by knowledge on the I/O analysis provided mainly by Miller and Blair (2009), two Brazilian studies that calculated the deficit cost by applying the I/O analysis are described in the present subsection; one study is the GCPS methodology in subsection 3.2.2.1, and the other is Vasconcelos and Carpio's methodology in subsection 3.2.2.2.

3.2.2.1 GCPS methodology

The GCPS study introduced in subsection 2.8.3.2.1 seems to be wide-ranging in terms of including several aspects of the economics discipline, such as social GDP and electricity price-demand elasticity. Despite that, some parts of the proposed methodology seem to present incoherencies that inhibit the use of this methodology as an insight to the method suggested by the present thesis. The main issues observed are the following:

- The I/O matrix analysis is not applied to calculate the global deficit cost, since the methodology presented elasticity concepts over matrix data, instead of directly applying Leontief analysis concepts;

- The price elasticity of the demand calculated is applied over the relation between the total production of each sector and the total electricity sector production, which in this context do not have a direct relation to the unitary prices.

3.2.2.2 *Vasconcelos and Carpio's methodology*

This subsection analyzes the methodology developed by Vasconcelos and Carpio, summarized in subsection 2.8.3.2.2. This critical analysis aims to better understand the study reasoning to improve the methodology development.

There were some noteworthy points, one of which regards the following main items of interest: GDP and electricity production. The article considers the primary inputs as GDP and imports, and the Brazilian 2009 I/O sector number 4 as the electricity data source. Nevertheless, imports do not add value to a region, only GDP does, and in the IBGE original matrix, economic sector number 4 aggregates electricity, gas, water, sewage treatment and urban cleaning. The article does not mention anything about disaggregating those data to work purely with GDP and electricity data.

Multipliers R_j are applied to each supply, reducing the amount of production destined to final demand and all other sectors that have demands for that production. This procedure considers only the primary impact of the final demand reduction in the total production of the corresponding sector. In other words, the article analyzed does not seem to consider that the other productive sectors, which supply the final demand of the sector required, should also suffer some production reduction, since the interindustry demand is lower.

Another point is that the methodology adopted does not seem to respect the production technology, since it simply reduces the amount of supply to a sector such that it does not maintain the proportion of inputs and considers that the output is the total production minus those reductions. However, the ideal is to maintain the proportions of the production matrix, which is equivalent to having a proportion of inputs to produce an output and it is not possible to change the amount of an input without changing the amount of the others. In other words, there would be a lack or a surplus of inputs and that is not permitted by a balanced matrix in which production must equal the demand.

To correct these proportions, following the article rationale, multipliers R in a column should be the same; for example, the highest R_j , which is the most restrictive. However, that would imply $R_j = q_j = c$, where c is some constant, which would be equivalent to all matrix values suffering the same percentage reduction.

In sum, apparently, the article chosen methodology does not make the most of the available I/O matrix data.

3.3 PROPOSED METHODOLOGY (1 OF 2) - GDP AND ELECTRICITY CONSUMPTION CORRELATION

To apply a simple regression over the GDP and electricity consumption, the first step consisted of collecting historical GDP and charge load data, which was accessed on the Ipeadata and EPE websites, respectively (EMPRESA DE PESQUISA ENERGÉTICA; MINISTÉRIO DE MINAS E ENERGIA, 2017; IPEADATA, 2017).

The first year adopted in this study is 1992, except data during an important outage that occurred in the country in 2001, which changed the consumption behavior. The last month considered in the analysis is December 2016.

The deficit cost calculation was simulated to be applied to each year from 2003 to 2017. For each calculation, data were considered from 1992 until the reference year. Using monthly GDP data was discarded in this study, because before data analysis and regression techniques be applied, there is a concern with the nature of the data content. The GDP data have a complex formation, including surveys and other data collection in various economic sectors, to determine the economic increase during a period. There is a natural difficulty in collecting precise variation data in the brief time window of a month. Moreover, the internationally agreed standard set of recommendations on how to compile measures of economic activity, called the National Account Systems (NAS), considers the quarterly periodicity. Additionally, this study also takes into consideration the application of an annual periodicity base.

Instead of using the nominal GDP series and then applying some deflator to obtain the real GDP, a series available on the Ipeadata website is used and presents the real GDP annual

variation. To directly obtain the real GDP from the national sources seems more reasonable to avoid a discussion about which deflator to use and the updated data availability issue.

Statistical references propose that, in most cases, a minimum of 30-sample items is desirable to provide a better data analysis quality, a number that is larger than that used in this study (TRIOLA, 2012).

After collecting the data, the log to base e of yearly differences of each series (GDP and consumption) were correlated, creating a log-log model as cited in subsection 3.2.1.2. Once the correlated data are dimensionless, the regression equation inclination parameter may be considered the linear elasticity between the GDP and the consumption, the formula of which is translated in Equation 17.

$$\varepsilon(y, w) = \frac{\Delta Y}{\Delta W} \quad (17)$$

where

$\varepsilon(y, w)$ – GDP percentage variation elasticity is due to the electricity consumption percentage variation

ΔY – GDP percentage variation between periods

ΔW – electricity consumption percentage variation between periods

The deficit marginal cost is then determined by the GDP monetary variation due to 1 MWh, as proposed by Equation 18.

$$c = \varepsilon(y, w) \frac{1}{w_{ref}} * y_{ref} \quad (18)$$

where

c - deficit marginal cost (R\$/MWh)

y_{ref} – GDP value in the reference year (R\$)

w_{ref} – electricity consumption value in the reference year (MWh)

The expression $1 / w_{ref}$ in Equation 18 captures the percentage variation that would be equivalent to 1 MWh in the total year consumption. The elasticity over $1 / w_{ref}$ obtains the GDP percentage variation corresponding to 1 MWh variation. Finally, the GDP in monetary terms is obtained when the correspondent GDP amount is considered in the reference year.

The objective of the present regression is to estimate the elasticity of GDP variation due to electricity consumption variation by identifying the equation angular coefficient. The average real GDP value is the same as the estimated GDP average only if the interception parameter is presented (GUJARATI; PORTER, 2011). Moreover, eliminating the interception parameter changes the slope to another value that may mistranslate the real data.

3.4 PROPOSED METHODOLOGY (2 OF 2) – INPUT-OUTPUT MATRIX

For applying the I/O analysis to calculate the electricity deficit cost, the ideal methodology to obtain the desired result would be to give a supply shock to the electricity sector and know the consequent impact over the GDP. However, the main theory in the literature presents a solution to measure the exogenous demand variation impact over production by using the Leontief inverse matrix, or measure GDP variation impact over total production by using the Ghosh inverse matrix.

Since the GDP (added value) is the targeted result of the present study, the algebraic manipulation of classic Leontief formulas to induce a stipulated supply shock was revealed to be simpler than using the Ghosh inverse, which requires a GDP variation shock as the exogenous input instead of as the result. Moreover, Ghosh proposes a supply side shock of added value items, although the present study goal is to provoke a supply side shock to the input of a productive sector.

The chosen approach applies the Leontief inverse by using an exogenous demand shock that provokes a predetermined requirement for the electricity total input. The GDP parcel of the resulting production variation to each economic sector is calculated by maintaining the same proportion observed at each year in the I/O matrix.

The year chosen to first explore the methodology proposed in this dissertation is 2013, because there is an I/O matrix and Leontief matrix ready to apply (GUILHOTO; SESSO FILHO, 2005; GUILHOTO; FILHO, 2010). Despite that, once the scenario option that seems better to solve the present research problem statement has been established, a deficit cost history is built based on the data from 2003 to 2013.

Although there is the possibility of working with a hybrid matrix, the transformation from BRL to MWh is punctually performed when necessary by an average tariff estimated to

obtain the result per MWh. Since there is no complex calculation using energy, the basic monetary input-output production data were considered sufficient to achieve the present study purposes.

The I/O calculation is linear by definition, being a static representation of a regional economy, Brazil in this case, and does not include the evolutionary process from that point, neither backwards nor forwards. In practical terms, the variation considered in the present methodology translates a production reduction due to a 1 MWh lack of electricity supply and its proportional added value (GDP) variation. This GDP variation includes the payments to households; nevertheless, the understanding of this study is that this variation, in practice, should not provide feedback to the productive system at this time since job losses are not considered. That leads to the option of applying the open model, which maintains household demand as an exogenous variable. The adopted assumption is to adapt to necessity by changing inputs; in sum, changing the I/O matrix does not necessarily imply less jobs and payments, but it likely exchanges those demanded sectors for others that may be substituted.

The possible changes between substitute products and technological changes are outside the present study scope. Another I/O matrix that translates the new interface between economic agents requires an update to the deficit cost value by reapplying the presented methodology to the new scenario. Most likely, there are other approaches to address the static situation issue; for example, Santos (2010) studied the field of influence method by which it is possible to identify the impact of a small technical coefficient change.

In sum, the total production amount decreases the equivalent of the national supply plus margins, taxes, imports and added value, which includes payments. This loss of payments included in the added value is part of the final resultant cost of deficit, which is exactly measured as the added value variation. In the case of the present study, the payment reduction should not be interpreted as real payment decreases, but as a proxy for the monetary measure of leisure lost, which, in this case, is included in the deficit total cost.

Subsection 3.4.1 explains the methodology adopted to disaggregate the electricity sector from gas and other utilities that appear together in the I/O matrix. In subsection 3.4.2, a methodology is proposed to verify the impact on GDP due to a variation on the electricity sector. The methodology proposed in Subsection 3.4.2 is applied to years 2003 to 2013, the same period that is applied to the methodology presented in Section 3.3 - *Proposed*

Methodology (1 of 2) - GDP and electricity consumption correlation for comparison purposes.

3.4.1 Electricity sector disaggregation

The ideal study would consider disaggregating electricity from natural gas and other utilities sectors, since this dissertation focuses exclusively on electricity. Despite this and the fact that there are some methodology notes published by IBGE, as cited in Subsection 3.1.1.3, the specific report references and numbers considered in those data compositions are not explicit to permit a better critical analysis of the adopted data treatment. Moreover, the data that concerns the gas sector is not detailed. For those reasons, the IBGE calculation reproduction to compose the electricity, gas and other utilities sectors was not achieved. To limit the present work scope, since this disaggregation topic would require an extended specific study, it is suggested as future work, and this dissertation scope simplifies the disaggregation by adopting an estimated percentage of sector production shares.

Moreover, for example, in 2012, approximately 40% of natural gas production is destined to electricity generation, and the I/O matrix for that year shows that nearly 30% of this aggregated sector production is consumed by itself (ASSOCIAÇÃO BRASILEIRA DAS EMPRESAS DISTRIBUIDORAS DE GÁS CANALIZADO, 2012). In that case, a lack of electricity would also cause a significant impact on the gas sector, implying less gas supply and, consequently, production, since the I/O matrix is balanced and linearly correlated. Nevertheless, probably in the Brazilian electricity sector reality a structural lack of hydropower would cause a higher coal and oil demand, as well as some increase in gas demand, although gas is more constantly used even in good hydrological periods due to its lower prices among thermo powerplants versus its equal supply security.

The assumptions of the electricity disaggregation from other sectors, to serve the finalities of this dissertation, were made based on the National Agency of Petroleum and Gas (ANP – Brazilian acronym) report published in 2017 and in 2013; in the case of previous years data, both reports contain historical values regarding the analysis period of 2003 to 2013. The sector names written in the uses and resources tables include “other utilities”, which were not considered in the present work because the sectors included in “other utilities”

were not defined in the literature. To disaggregate electricity, data from the I/O matrix sector were categorized as follows: electricity and an aggregated second sector that contains all other data excluding electricity.

The ANP report data regarding the gas sector present the total Brazilian gas volume production and the national average price. These data are used to indicate the gas production in monetary units. For 2010 to 2013, this is sufficient to disaggregate the sector, since only two items are considered in these matrices: gas and electricity.

In the case of years 2003 to 2009, water, sump and urban sewage are included at the same sector together with electricity and gas. In this case, the more recent years (2010 to 2013) are used as a base to extrapolate to previous years, since the data regarding those other sectors are already disaggregated in these original matrices. The average of the percentage participation of those sectors over a total that includes gas and electricity is applied to all previous years of this study. By knowing this percentage plus the gas production for those years, the electricity sector total production value is obtained by exclusion. Table 7 presents the calculated participation of those sectors that is applied to the disaggregate electricity in the I/O matrices used in present study.

Table 7 – I/O matrix electricity sector disaggregation

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas (%)	5,2%	4,2%	4,5%	4,4%	4,8%	7,4%	6,8%	7,2%	6,8%	5,9%	7,8%
Water, sump and urban sewage (%)	22,4%	22,4%	22,4%	22,4%	22,4%	22,4%	22,4%	n/a	n/a	n/a	n/a
Electricity (%)	72,3%	73,4%	73,1%	73,1%	72,8%	70,2%	70,8%	92,8%	93,2%	94,1%	92,2%

Source: calculated by the author.

3.4.2 Methodology

The GDP is determined by the added value over production, which is the sum of personal payments, gross operating surplus, mixed incomes and direct taxes over production less subsidies. Production technical coefficient matrix A is determined by the intermediate production consumption at basic prices over the total sector production X in market prices, which includes imports and its taxes, commercial and transport margins, and added value. Another technical coefficient matrix R is created considering the added value over the same total production of each economic sector X. To fit the matrix algebra, the added value technical coefficient matrix R is diagonal as shown by Equation 19.

$$R = \begin{pmatrix} r_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & r_n \end{pmatrix} \quad (19)$$

where

R = added value coefficient diagonal matrix

$$r_j = \frac{AV_j}{X_j}$$

AV_j = added value in sector j

X_j = total sector j production in market prices

To determine the sector demand impact in economic production, a demand vector containing the desired demand variation of each sector post-multiplies the Leontief matrix. The Leontief matrix presents production variation that each sector in lines suffer due to a unitary demand shock in the sector presented in the column. Since the interest is added value variation, the R matrix should premultiply the Leontief matrix. This is presented in Equation 20.

$$\Delta GDP = R * L * \Delta D \quad (20)$$

or

$$\Delta GDP = R * \Delta X$$

The first strong assumption is coherent to the I/O analysis application that implies that it is not possible to alter a single sector output without secondarily shocking other economic sectors. To reduce an output implies reducing not only the final demand but also the outputs of other industries that serve as inputs to those reduced final products, since the system is in equilibrium.

The second assumption is the proportion of exogenous demand shock to guarantee a total electricity industry output reduction equivalent to 1 MWh. To shock the demand of sectors other than electricity is equivalent to imposing a rationing scheme in which various industries have their final outputs reduced to consume less electricity.

Four scenarios are tested for 2013 to choose the most adequate scenario to be adopted for the other years calculations. The first scenario maintains the demand proportions between

the sectors. The second forces the direct final demand reduction of the electricity sector exclusively, as if all electricity rationing schemes are placed on the final consumer. The third prioritizes the rationing of those with smaller proportions between the contribution to GDP creation and electricity consumption. Finally, the fourth criteria reduces the electricity input of each sector proportionally to its respective electricity consumption. The latter is divided in two subscenarios as follows: the first includes a final demand direct rationing of electricity, while the second does not, which means that final demand is affected only indirectly by reducing the total production of all sectors that have electricity as an input. Table 8 summarizes the proposed scenarios.

Table 8 – Scenario descriptions

Scenarios	
1	Maintain final demand proportion between I/O matrix economic sectors.
2	Final demand variation exclusively on the electricity sector.
3	Assign for each economic sector a final demand variation proportionally to the reason of the electricity consumption over GDP contribution.
4	4a. Final demand is directly reduced by the same proportion for all economic sectors.
	4b. Only productive sectors are directly rationed.

Source: the author.

Rationing for the third criteria means to target sectors that have a high electricity demand and do not generate much GDP. The expected result in this case is a smaller deficit cost, as concluded by Nooij in his study about efficient versus random rationing actions (DE NOOIJ; LIESHOUT; KOOPMANS, 2009).

The demand variation in each sector should be the one that results in a unitary production variation of the electricity sector, which means that electricity sector production in vector X should be equivalent to 1 MWh ($\Delta x_e = 1$ MWh translated in monetary units). The

unitary cost of a MWh for a given year is considered as a weighted average between the regulated electricity tariff and the average of the four submarkets short term market price, in proportions consistent to the consumption volume in the regulated and free market, respectively. This calculation is applied to each year included in the analysis horizon to determine the average value (R\$) of 1 MWh.

Scenarios 1 to 3 were calculated by the methodology translated by Equations 21 to 24, which consider the Leontief matrix, while the fourth scenario calculation is different, as explained in sequence.

The basic formula described in Equation 21 applies the Leontief inverse matrix, from which a linear equation system is built.

$$\Delta X = L * \Delta D \quad (21)$$

The number of unknown variables in the linear equation system is the same as the productive sectors that compose the I/O matrix. If n is the number of existing economic sectors in an I/O matrix, then in the ΔX vector, there are $n-1$ unknown variables, since the only known variable in the ΔX vector is the electricity production x_e , exogenously determined as the desired shock equivalent to 1 MWh (in monetary units).

The demand variation vector is also unknown. An assumption in this case is the settlement of the proportion between sector demands. In scenario 1, the demand variation of the economic sectors respects the initial consumption habit proportions between them. In scenario 2, the final demand of all sectors is zero except for the electricity sector; and in scenario 3, the demand proportion between the sectors follows the proportion of how much electricity is used by each sector in relation to the sector GDP generation. In scenario 4, differently from the others, the final demand is a consequence, since the sector production and not the final demand is the established information to compose the scenario.

To translate the logic in scenarios 1 to 3 to an equation system, a constant c that multiplies the proportion demand vector is considered as the last system incognita to complete the n unknown variable. Hence, all items of the total demand variation vector (ΔD) are understood in terms of a proportion related to c . Equation 22 to Equation 24 shows how the linear equations system is built and solved; notice that Equation 22 details Equation 21.

$$\begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_e \\ \vdots \\ \Delta x_n \end{bmatrix} = \begin{bmatrix} l_{11} & l_{12} & \dots & l_{1n} \\ l_{21} & l_{22} & \dots & l_{2n} \\ l_{e1} & l_{e2} & \dots & l_{en} \\ \vdots & \ddots & \ddots & \vdots \\ l_{n1} & l_{n2} & \dots & l_{nn} \end{bmatrix} * \begin{bmatrix} \Delta d_1 \\ \Delta d_2 \\ \Delta d_e \\ \vdots \\ \Delta d_n \end{bmatrix} \quad (22)$$

Suppose that Δx_e is known - it is the desired shock; in the case of the real study, it is the electricity sector production variation that is stipulated exogenously: $\Delta x_e = 1$ MWh (as previously described, for each year, there is a monetary value equivalent to 1 MWh to be applied in this calculation). Additionally, suppose that c is the constant to be used in the calculation of all sector demand proportions and that l_{ij} composes the known Leontief inverse matrix. A vector of demand proportions (P) is built as presented in Equation 23 to be replaced in Equation 22.

$$\Delta D = P * c \quad (23)$$

$$P = \begin{bmatrix} \Delta d_1 / c \\ \Delta d_2 / c \\ \Delta d_e / c \\ \vdots \\ \Delta d_n / c \end{bmatrix}$$

$$p_1 + p_2 + p_e + \dots + p_n = 1$$

In sum, $p_j = \Delta d_j / c$ and the resultant linear equation system is presented in Equation 24.

$$\left\{ \begin{array}{l} \Delta x_1 = (l_{11} * p_1 + l_{12} * p_2 + l_{13} * p_3) * c \\ \Delta x_2 = (l_{21} * p_1 + l_{22} * p_2 + l_{23} * p_3) * c \\ (R\$ equivalent to 1 MWh) = (l_{e1} * p_1 + l_{e2} * p_2 + l_{e3} * p_3) * c \\ \vdots \\ \Delta x_n = (l_{n1} * p_1 + l_{n2} * p_2 + l_{n3} * p_3) * c \end{array} \right. \quad (24)$$

In matrix form: $\Delta X = \Delta X_p * c$, where $\Delta X_p = L * P$. Notice that ΔX_p is a proportional total production variation vector related to a demand shock or variation that forms one monetary unit. This unitary total demand variation is translated by vector P , where the sum of all elements results in 1.

The unknown variables of Equation 24 are c and $\Delta x_1, \Delta x_2 \dots \Delta x_n$, except for Δx_e . The practical procedure applied to solve this problem was first to determine a primary ΔX_p vector, considering $\Delta X_p = L * P$. Then, the Excel recursive function that stipulates a target number by varying some other cell value was applied, considering that $\Delta X = \Delta X_p * c$. In this example, the target number would be $\Delta x_e = 1$ MWh (in monetary units), which should be achieved by varying c . By the end of this procedure, c is known, and consequently, the other ΔX values are also known, except for the stipulated unitary Δx_e .

After that, Equation 20 is applied to determine the final objective, which is the total added value that consists of the sum of all ΔGDP vector elements.

The fourth scenario is calculated in a different manner than the other three scenarios. The proportion maintained in the case of the fourth scenario is related to the electricity input to each sector. The total cut off is stipulated as the monetary value that represents one MWh, a value which is distributed proportionally to the electricity input of each sector. This means that all sectors would have the same reduction percentage. The resultant cut off value of each sector divided by the respective technical coefficient related to the electricity input (see Equation 13 for the technical coefficient matrix) results in the total production variation of each sector that is necessary to be reduced to determine the targeted electricity input reduction.

In the case of the fourth scenario, the Leontief matrix is not necessary since the GDP variation can be calculated directly over the total production reduction obtained. The final demand is known if the resulting total production is premultiplied by the matrix $(I-A)$.

4 ANALYSIS

The present chapter aims to present the results of the applied methodologies described in Sections 3.3 and 3.4 and to analyze them. Subsection 4.1 describes the GDP and electricity consumption linear regression methodology, while Subsection 4.2 presents the I/O approach results.

In Subsection 4.2 there are also simulations of the impact of applying the estimated deficit cost. These simulations are performed by the software Newave, program which is officially adopted to base decisions about the Brazilian power system operation.

4.1 ANALYSIS - GDP AND ELECTRICITY CONSUMPTION CORRELATION

The quarterly analysis resulted in a highly dispersed plot, making it meaningless to apply regression analysis. The annual analysis seems to configure a more well-behaved data correlation; nevertheless, there are four years in which the data have a stretched plot format. Despite those outliers, the plotted points seem too dispersed to provide a reliable regression line.

Figure 7 illustrates the quarterly data plot in which no regression curve seems applicable. The input data included the GDP and electricity consumption percentage variation from 2003 to 2016.

Figure 7 - GDP vs electricity consumption quarterly variation plot (data from 2003 to 2016).

Source: the author's elaboration.

Figure 8 presents the annual analysis using the data from 1992 to 2016, disregarding 2001 as an outlier. Notice that although the data seem to be more well-behaved than in Figure 7, if disregarding the extreme points, there is no pattern that would lead to a reliable correlation. The data group without those outliers is highlighted in Figure 8.

Figure 8 - GDP vs electricity consumption annual variation plot (data from 1992 to 2016).

Source: the author's elaboration.

The annual data history is built and presented in Table 9 from 2003 to 2017, including the calculated R^2 parameter that demonstrates the weak correlation between the GDP and the consumption data. The calculation included the logarithm to base e ($\ln$) over the data variation because of the motives presented in Subsection 3.2.1.2. The variation input data are provided in Table A- 1 in the ANNEX.

Table 9 – Linear regression of annual GDP and electricity consumption variation applied to each year from 2002 to 2016

year of reference	Sample size	GDP (BRL)	Electricity consumption (MWh)	Elasticity (angular coefficient)	R ²
2002	11	1,488,787,100,000	324,293,786	0.7761	0.29
2003	12	1,717,950,400,000	342,274,598	0.6212	0.19
2004	13	1,957,751,100,000	360,009,790	0.7253	0.21
2005	14	2,170,584,600,000	375,260,627	0.7158	0.20
2006	15	2,409,450,100,000	390,020,591	0.6681	0.18
2007	16	2,720,262,900,000	412,204,803	0.8029	0.23
2008	17	3,109,802,900,000	428,326,630	0.7260	0.18
2009	18	3,333,039,300,000	426,105,561	0.6796	0.32
2010	19	3,885,847,100,000	464,782,688	0.7331	0.45
2011	20	4,373,658,000,000	481,054,761	0.7141	0.43
2012	21	4,805,913,100,000	498,475,754	0.7266	0.44
2013	22	5,316,455,100,000	516,060,041	0.7218	0.44
2014	23	5,687,309,000,000	532,441,486	0.7532	0.44
2015	24	5,936,677,600,000	524,467,871	0.8608	0.60
2016	25	6,266,739,400,000	519,915,538	0.9290	0.67

Source: Calculated by the author based on Ipeadata (2017) for GDP and EPE (2017) consumption data.

By using the acceptable Pearson correlation coefficient (r) suggested by Triola (2012) in Chapter 10, for a sample of 17 data pairs, a r greater than 0.482 presents a 5% chance of being uncorrelated. That means that this methodology could be acceptable for 2009 to 2016. However, by expurgating those four points out of circle presented in Table 9, the r obtained is bigger than the acceptable exclusively in 2014, becoming 0.467. Hence, the correlation methodology suggested by this research did not present results considered proper for comparison to the 2003 to 2013 outcomes obtained by the other proposed methodology application, which is described in the next subsection.

Although the inconclusive analysis is based on simple regression, Schmidt and Lima (2004) seem to have studied a multiple regression to explain the electricity demand variation, which includes variables of the tariff, family income or GDP in the case of industrial and commercial consumers, electrical equipment prices and electricity substitute commodities. In this case, the GDP explains part of the consumption variation, while in the present work, the objective is the opposite: to measure the GDP variation due to consumption.

The I/O matrix is a static and balanced system, which allows better economic analysis; moreover, the I/O approach isolates the electricity impact over the GDP, while in the

correlation methodology, it is not possible to isolate the electricity sector impact over the GDP (VARIAN, 2015). Therefore, the next section explores the analysis of the I/O analysis methodology application.

4.2 INPUT OUTPUT MATRIX

The unitary electricity shock is considered as a weighted average of the Brazilian short market price, calculated by using the submarket simple averages, and the regulated tariff average informed by ANEEL (AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA, 2017; CÂMARA DE COMERCIALIZAÇÃO DE ENERGIA ELÉTRICA, 2017). The percentage of price composition follows the approximate proportion of the free and regulated market of each year, informed by the online CCEE Market Report (CÂMARA DE COMERCIALIZAÇÃO DE ENERGIA ELÉTRICA, 2017). The resultant unitary price per year is present in Table A-2 (ANNEX), a value which is inserted as the Δx_e target while the constant c varies to achieve the target value.

The first step was to evaluate the scenario differences by applying the methodology for each scenario in 2013 case. This resulted in a Brazilian deficit cost of R\$ 6,982 / MWh in scenario 1, R\$ 137 / MWh in scenario 2, and scenario 3, R\$ 392 / MWh. Finally, in scenario 4a, the Brazilian deficit cost resulted in R\$ 6,886 / MWh, with the final demand directly participating in the rationing, and in Scenario 4b, R\$ 9,957 / MWh by distributing the rationing target exclusively among the productive sectors. Table 10 summarizes the result obtained for each scenario.

Table 10 – Deficit cost for each scenario in 2013

Scenarios		Deficit Cost (BRL/MWh)	Observations	
1	Respect final demand proportion between I/O matrix economic sectors.	6,982	-	
2	Final demand variation exclusively on the electricity sector.	137	-	
3	Assign for each economic sector a final demand variation proportionally to the reason of the electricity consumption over GDP contribution.	392	-	
4	The same electricity reduction proportion is applied to all productive sectors.	4a. Final demand is directly reduced by the same proportion of all economic sectors.	6,886	Result is similar to Scenario n.1; the difference is due to existence of sectors for which electricity input is zero.
		4b. Only productive sectors are directly rationated.	9,957	Total rationed electricity amount is above the equivalent of 1 MWh.

Source: the author

The intention of scenario 4b did not work in practical terms because there is a final demand shock that may result in the reduction proposed by the rationed sectors. That means that productive sectors reduce the equivalent to 1 MWh, but by using the technical coefficient matrix A that maintains the proportions of the I/O matrix elements, the total electricity production reduction to attain the scenario impositions results in a larger value than is necessary, in this case, R\$ 370 / MWh, while the 2013 MWh electricity average price is R\$ 256 / MWh. The difference represents the consequent direct reduction of the final demand necessary to maintain the I/O matrix equilibrium. Scenario 4b is discarded due to the larger resultant deficit cost, together with the electricity restriction that is larger than necessary, in addition to the larger total demand and total production reduction.

The results of scenarios 1 and 4a are very similar; the difference is that the domestic services sector is not demanded in scenario 4a since the distribution was made based on the electricity input to each sector, and the domestic services sector does not demand electricity. The difference in the results between these scenarios is exactly the GDP value regarding the domestic services sector. Scenario 4a seems to make more sense seeing that neither the domestic services nor the electricity sector interferes or is an input to the other. Therefore,

there would be no reason to restrict the domestic services final consumption as considered in scenario 1.

Scenario 2 resulted in the lowest deficit cost among the scenarios studied. The Leontief inverse matrix has values above 1 diagonally and lower than 1 in other positions, which means that reducing the electricity primary demand is very effective to reduce the total electricity production. To depend on secondary demand requires more of the total production from several sectors to achieve the proposed total electricity reduction.

For scenario 3, despite resulting in an almost three times greater deficit cost than that in scenario 2, the electricity final demand variation is approximately 75% of that required in scenario 2. In monetary units, there is a R\$ 181 direct reduction of electricity by the final demand in scenario 2, while it is R\$ 134 in scenario 3. Since the electricity production reduction is the same in both scenarios, totaling R\$ 256, other economic sectors need more variation in scenario 3 to achieve the same value (equivalent to 1 MWh), a fact that can be observed through the three-times larger demand reduction in scenario 3 when compared to scenario 2.

Scenarios 2 and 3 do not seem to be of easy application because both require a larger proportional effort from some sectors than from others, which may be seen as unfair politics. Finally, the more realistic scenario is number 4a, which imposes the same rationing percentage to all the productive sectors and final demand.

Therefore, the methodology used to calculate scenario 4a was applied to years 2003 to 2013 to identify how the deficit cost would evolve throughout the years, as presented in Table 11.

Table 11 – Electricity deficit cost for years 2003 to 2013 by applying I/O analysis – nominal values

Deficit Cost	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
(R\$ / MWh)	3,369.37	3,462.48	3,667.34	4,019.02	4,488.59	4,927.98	4,833.59	4,982.76	5,108.94	6,049.43	6,886.20

Source: the author.

Figure 9 compares the results to the following official values: the lower and the higher level published by ANEEL, and the single level calculated and published by EPE. The single level is calculated since 2006 (despite publishing gaps in 2007 and 2010), which occurred to be officially adopted by ANEEL as the input parameter to the system computational

simulations since 2017. Hence, the official deficit cost may be underestimated since it represents a maximum of 15% of the suggested methodology results.

Figure 9 – Results comparison – nominal values

Source: the author based on ANEEL and EPE data, in addition to the author's own generated data.

To measure the impact of these results, the Brazilian power system was simulated by inputting the results into the officially adopted computation software Newave. Then, the output parameters were compared to those actually used at that time. To use the most recent versions of the computational software, Newave 22 and Newave 23, the simulations were developed to years 2016 and 2017, respectively. Once the results obtained by the proposed methodology showed some similarity to the higher-level deficit cost, this was the value used as a single level for comparison purpose. Figure 10 shows the frequency of the percentage comparison of the ANEEL higher-level deficit cost data and the results obtained by applying the methodology presented in this thesis; the average difference is 9%.

Figure 10 – Histogram of the percent difference between the ANEEL higher deficit cost level value and the results obtained by applying Martins methodology (2003-2013).

Source: the author.

Table 12 summarizes the scenarios considered for comparison purposes, in which the only parameter altered is the deficit cost. The “higher level” scenarios represent the methodology supported by this research, although not calculated by the proposed methodologies.

Table 12 – Deficit cost scenario simulations

Scenario (R\$ / MWh)	Marginal deficit cost - levels				
	Single	First	Second	Third	Fourth
2017 Single level	4650.00	-	-	-	-
2017 Higher level	8595.40	-	-	-	-
2017 Four level	-	1677.81	3619.59	7564.63	8595.40
2016 Single level	4000.00	-	-	-	-
2016 Higher level	8050.39	-	-	-	-
2016 Four level	-	1571.42	3390.08	7084.98	8050.39

Source: EPE and ANEEL data.

Two other scenarios were simulated for the same period; one considering the four-level deficit cost curve, and the other, the single level published by EPE. Since the submarket SE/CO is the most significant in terms of reservoir capacity and electricity demand, it was the focus of the analysis that aimed to understand the impacts of different deficit costs.

The simulation horizon is 5 years ahead; the first year was analyzed for operational data, since the results of the first period better simulates the real initial situation, while the more distant periods from the origin tend to converge independently of the initial scenario. For costs data and unsupplied energy, the comparison considers the total period of 5 years.

The higher-level deficit cost scenario presents the higher CMO as shown in Figure 11, fact which demonstrates the influence of the deficit cost on the energy price. Moreover, the higher deficit cost resulted in a lower deficit risk when compared to the other two scenarios, as shown in Figure 12. Figure 13 and Figure 14 show that the hydro generation and hydro reservoir levels are relatively stable between the scenarios for each year; therefore, to result in the lower unsupplied energy amount presented in Table 13, thermopower dispatch is greater, which is shown in Figure 15.

Figure 11 - CMO output comparison (SE/CO submarket).

Source: Elaborated by the author based on Newave software output.

Figure 12 – Deficit risk (%) comparison (SE/CO submarket).

Source: Elaborated by the author based on Newave software output.

Figure 13 – Energy storage - hydro reservoir (SE/CO submarket).

Source: Elaborated by the author based on Newave software output.

Figure 14 – Hydro generation (SE/CO submarket).

Source: Elaborated by the author based on Newave software output.

Figure 15 – Thermopower generation (SE/CO submarket).

Source: Elaborated by the author based on Newave software output.

Table 13 – Unsupplied energy (SIN)

Unsupplied energy (MWa)	
2017 Single level	3.2
2017 Higher level	2.3
2017 Four level	7.0
2016 Single level	4.1
2016 Higher level	2.2
2016 Four level	6.6

Source: Elaborated by the author based on Newave software output.

To complement the analysis, the total operational cost, including the SIN, is detailed in Table 14 – Total operational cost composition - 5 years study. Moreover, a comparison of the proposed scenario (higher-level deficit cost) to the other two scenarios (single level and four level deficit cost) is shown in Table 15 and Table 16 – Higher level scenario comparison to the single level and four level scenarios .

Since the total deficit cost is the multiplication of the unsupplied energy to the marginal deficit cost, by increasing the marginal deficit cost, the system tries to equilibrate costs by lowering the unsupplied energy. The increase of thermopower generators seems necessary to achieve the unsupplied energy reduction, since Table 15 presents it as the most significant cost parcel - more than 50% in all cases – and Table 16 presents a growth of more than 1% when comparing the higher-level scenario to the others in the same year.

In parallel with increasing the thermopower generation, the reservoirs are managed to remain at an acceptable security level, which, especially in 2016, required paying higher penalties than those in 2017 simulations for not following water management requirements. Figure 14 shows that, despite January having a similar reservoir level for both years, throughout the year, the 2017 levels were significantly below those of 2016 when comparing the same operational months.

Table 14 – Total operational cost composition - 5 years study (R\$ million)

(R\$ million)	2017 Single level	2017 Higher level	2017 Four level	2016 Single level	2016 Higher level	2016 Four level
Thermopower generation	16127.01	16481.27	15882.73	14421.00	14567.82	14349.65
Deficit	767.26	1019.78	829.68	903.65	887.17	826.36
Water discharge	0.89	0.91	0.9	0.91	0.92	0.92
Violation others	173.34	210.28	266.47	2431.68	2686.32	2493.46
Violations minimum water discharge	534.31	481.64	530.98	9837.44	9815.31	9824.62
Interexchange	1.37	1.37	1.37	1.33	1.31	1.31
Water discharge - without reservoir	1.4	1.41	1.39	1.49	1.49	1.48
Violation minimum hydro generation	587.16	592.89	635.92	874.73	667.88	802.8
Total	18192.74	18789.55	18149.44	28472.23	28628.22	28300.6

Source: Elaborated by the author based on Newave software output.

Table 15 – Total operational cost composition – 5 years study (%)

	2017 Single level	2017 Higher level	2017 Four level	2016 Single level	2016 Higher level	2016 Four level
Thermopower generation	88.6%	87.7%	87.5%	50.6%	50.9%	50.7%
Deficit	4.2%	5.4%	4.6%	3.2%	3.1%	2.9%
Water discharge	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Violation others	1.0%	1.1%	1.5%	8.5%	9.4%	8.8%
Violations minimum water discharge	2.9%	2.6%	2.9%	34.6%	34.3%	34.7%
Interexchange	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Water discharge - without reservoir	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Violation minimum hydro generation	3.2%	3.2%	3.5%	3.1%	2.3%	2.8%
Total	100%	100%	100%	100%	100%	100%

Source: calculated based on the Newave software output.

Table 16 – Higher level scenario comparison to the single level and four level scenarios

	2017 higher level costs subtracted from:		2016 higher level costs subtracted from:	
	2017 single level	2017 four level	2016 single level	2016 four level
Thermopower generation	2.1%	3.6%	1.0%	1.5%
Deficit	24.8%	18.6%	-1.9%	6.9%
Water discharge	2.2%	1.1%	1.1%	0.0%
Violation others	17.6%	-26.7%	9.5%	7.2%
Violations minimum water discharge	-10.9%	-10.2%	-0.2%	-0.1%
Interexchange	0.0%	0.0%	-1.5%	0.0%
Water discharge - without reservoir	0.7%	1.4%	0.0%	0.7%
Violation minimum hydro generation	1.0%	-7.3%	-31.0%	-20.2%
Total	3.2%	3.4%	0.5%	1.1%

Source: calculated based on the Newave software output.

In 2017, the deficit total cost is 22% higher on average for the higher marginal deficit cost level; nevertheless, the deficit cost represented approximately 5% of the total operational cost. For 2016, this proportion is nearly 3%, while the variation was under 7% between the scenarios.

In sum, although the apparently different strategy adopted by each version of Newave to optimize the total cost routine, the result for both years is a better system security regarding a lower deficit risk and unsupplied energy, while an increase in the total operational cost and, consequently, the CMO when considering a higher deficit cost.

An additional comment about the I/O analysis presented here is that a more agile availability of data, the I/O matrix in this case, is necessary to better apply this methodology. In the present work, the year of calculation and application are considered the same, although in reality there would be some period mismatch.

5 CONCLUSIONS

This research objective was to ascertain and suggest the possibilities of improving the electricity deficit cost estimation in Brazil by using the input-output analysis approach. The secondary objectives were to verify the causes and applications of the deficit cost value, to review the state-of-the-art methods in the study field and to analyze calculation proposals applied to Brazil other than the officially adopted calculation.

The electricity deficit cost value may be applied to support decisions of maintenance and investments, to support decisions of where and when there should be an electricity cut off, and to define the energy-trading price.

There are different causes of the electricity deficit; some of them affect the supply in the short term and others, in the long term. The case of Brazil shows that the lack of electricity may occur structurally, especially due to poor hydrologic periods associated with an inefficient system expansion strategy. The fact that the major cause of the electricity deficit throughout the world is more punctual due to a more stable supply that is based primarily in thermos, the most applied methodologies observed in the international literature, which are based on surveys of consumers, seems to be less applicable to Brazil.

The present work uses other studies and ideas as a base to develop a deficit cost calculation methodology. Two methodologies are explored herein as follows: one calculates the deficit cost by correlating the consumption and GDP series, and the other applies basic concepts of the Leontief I/O analysis to measure the GDP impact due to the lack of one MWh. The I/O analysis seems more reliable for permitting a clearer distinction of the electricity sector impact on the GDP composition, while the regression methodology is simpler in regard to this kind of assumption. For the present study, the correlation coefficient calculated to explain the parcel of impact of the electricity sector over the GDP did not demonstrate a possible correlation between the analyzed data, making this approach inconclusive.

The I/O analysis presented similar results to the ANEEL published higher-level deficit cost when considering four levels, with a 9% difference on average. By simulating scenarios with the results as inputs of the Newave software for the years 2017 and 2016, the efforts of reducing the lacking energy amount when the marginal deficit cost is higher were observed.

Hence, it is possible to optimize the total operational cost by lowering the lack of electricity that is multiplied by the deficit cost, substituting those values for a lower thermopower generation cost. Moreover, the software maintains the reservoir levels and includes violation costs regarding water management in the operational account.

In conclusion, a higher electricity deficit marginal cost implies a higher operational cost and system security through a total cost optimized solution that considers dispatching more power generators instead of permitting a larger energy deficit. In Brazil, the more adequate marginal value for the electricity deficit is the amount of GDP the country loses by not producing goods and services due to the missing 1 MWh. This research suggests that the officially adopted cost is underestimated; in 2013, for example, it should have been BRL 6,886 / MWh to better translate the country productive situation, a value that is more than two times that calculated by the EPE.

There is some possible future work to improve the present research. This includes but is not limited to the following suggestions: (i) to reproduce the proposed methodology over an updated Brazilian I/O matrix; (ii) to improve the methodology used to segregate the natural gas and electricity sectors; (iii) to improve the I/O changes due to substitute products of the electricity; (iv) to explore possible different deficit costs depending on the deficit level; (v) to study the electricity deficit cost value in Brazilian isolated areas (not interconnected to SIN); and (vi) to verify the applicability and importance of using the GDP at social prices.

Since this dissertation focus is the methodologies applied in Brazil, a further study could specifically verify the methodologies applied to other world countries that has hydro as the predominantly electricity source, and test them in the Brazilian scenario.

Moreover, the author suggests to investigate an alternative way of calculating the deficit cost by using the I/O analysis approach that applies the field of influence methodology, which could also be combined with some computable general equilibrium models.

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ANNEX

Table A- 1: Annual variation of the electricity consumption and GDP

Year	Electricity consumption variation	GDP variation
1992	2.26%	-0.24%
1993	4.64%	4.25%
1994	3.58%	5.12%
1995	6.01%	3.74%
1996	4.86%	1.98%
1997	6.12%	2.91%
1998	4.19%	0.62%
1999	2.84%	0.96%
2000	5.08%	3.93%
2002	4.73%	3.58%
2003	5.54%	1.23%
2004	5.18%	5.66%
2005	4.24%	3.01%
2006	3.93%	3.69%
2007	5.69%	5.80%
2008	3.91%	4.68%
2009	-0.52%	-0.10%
2010	9.08%	6.98%
2011	3.50%	3.74%
2012	3.62%	1.61%
2013	3.53%	2.88%
2014	3.17%	0.46%
2015	-1.50%	-3.15%
2016	-0.87%	-3.14%

Source: Elaborated by the author based on Ipeadata (2017) for GDP and EPE (2017) for consumption data.

Table A-2: Average value of the MWh (R\$ / MWh)

Avg. Value	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
R\$ / MWh	168.58	181.76	188.86	201.44	211.71	216.85	205.6	216.39	213.06	258.95	256.07

Source: calculated by the author based on ANEEL and CCEE data.