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Socioeconomic and environmental consequences of a new law for regulating distributed generation in Brazil: A holistic assessment

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ABSTRACT

Since 2012, prosumer compensation in Brazil has been based on net metering. However, a new law (Ordinary Law 14300/2022) was recently approved by the Brazilian Congress to decrease financial compensations for electricity injected into the grid. Studies on distributed generation system economic feasibility impacts in light of this new regulation are quite common. However, there is a research gap with respect to holistic assessments. This paper holistically analyzes the long-term consequences of this new law for regulating on-grid renewable distributed generation in Brazil. The methodology was mainly based on three models/techniques, i.e., the optimized tariff model (socioeconomic regulated electricity market model), the Bass diffusion model (time-series forecasting for integrated distributed generation), and life cycle assessment (an environmental impact analysis technique). These methodologies allow us to evaluate regulatory impacts on several aspects like the distributed generation business itself, market surpluses and welfare, regulated tariffs, social inequality, and the environment. These methodologies were applied to 35 Brazilian concession areas with available data. The results show that the new law successfully mitigates tariff increases and reduces social inequality, which are its main goals. By contrast, there are significant negative implications to the distributed generation business, market welfare, and the environment, since socioeconomic welfare losses at 2.12 billion (BRL/year) or 0.42 billion (USD/year), and emissions at 0.35 (Mt CO_{2eq}/year) are estimated. Our assessment also shows that it would be slightly premature to implement this new law in most concession areas.

1. Introduction

In 2012, the Brazilian Electricity Regulatory Agency (ANEEL) published its first specific regulation of on-grid renewable distributed generation (DG) in Brazil. Normative Resolution 482 (ANEEL, 2012), stated that compensation for electricity injected into the grid by prosumers would be calculated using the net metering policy, i.e., a 100% compensation for all injected electricity. In 2015, Normative Resolution 687 was published (ANEEL, 2015), to review the previous resolution. Several modifications were made, e.g., defining micro/mini generation and new investment modalities like shared/cooperative generation. However, Normative Resolution 687 kept net metering, which is currently still valid, i.e., net metering is currently Business as Usual (BAU) for DG regulation in Brazil. Nevertheless, this policy will be changed in the short term given increased DG deployment and stakeholder pressures (ANEEL, 2019a). Compensation will be set at less than 100% to safeguard distribution companies and conventional consumers (consumers who do not own DG systems). More specifically, the new regulation will seek to mitigate the death spiral process (Castaneda et al., 2017), which occurs when tariffs must be continually increased to maintain financial economical equilibrium (FEE) among concessionaires in function of substantial DG penetration. This process naturally occurs at 100% compensation, since decreased revenue tends to be more influential (Castaneda et al., 2017), although DG does decrease several costs e.g., grid costs, energy losses, and operational costs. However, we should note that the death spiral process is a concern for substantial DG penetration only.

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List of parameters

Parameter/variable	Description
P_{SH}	Amount of peak sun hours
A_I	Average income in per unit
n	Compensation parameter
a	Consumers/prosumer avidity
b	Consumers/prosumer satiety
ECA	Consumers/prosumer surplus
C_D	Cost of DG system acquisition/operation
s_1	Cost parameter of DG systems acquisition/operation
C_I	Costs related to mobile and real estate infrastructure
$F(t)$	Cumulative distribution function
ε	Demand elasticity
g	DG energy loss influence parameter (proportional)
f	DG energy loss influence parameter (quadratic)
e'	DG operational cost influence parameter
C	Distribution company costs
k	Distribution company hurdle rate
EVA	Distribution company surplus
U	Economic utility function
C_C	Electricity purchase costs
p	DG null penetration energy loss cost parameter
E_G	DG generated electricity
E_G'	Hypothetical PV system generated electricity
B	Grid investment
q_B	Imitation parameter
p_B	Innovation parameter
m_p	Market potential
m_{mf}	Maximum market fraction
$m_{mf(M)}$	Mean maximum market fraction of the country
$P_{BS(M)}$	Mean payback sensibility of the country
C_A	O&M costs
e	Operational costs parameter
B^*	Optimal grid investment
E	Overall consumed electricity (grid and DG)
P_{BS}	Payback sensibility
P_{BT}	Payback time
PEI	Performance index
η	PV system efficiency
P	Hypothetical PV system rated output power
T	Regulated tariff
R	Revenue
E_S	Sectorial charges
l	Share of self-consumption
EWA	Socioeconomic welfare
C_T	Transmission costs
t	Tributes over profit
μ	Tributes over sales

Table 1
Innovations with respect to existing literature.

Item	Costa et al. (2019)	This paper
Analyzed regulation proposals	Public Hearing 25/2019	Ordinary Law 14300
Installed DG capacity	Three scenarios with arbitrary capacities	Forecasted based on a recognized model (BDM)
Results	Static	Dynamic, i.e., as functions of time
Number of analyzed concession areas	3	35
Impacts on the distributed generation business	Not addressed	Directly quantified
Impacts on DG demand in the whole electricity market (market player surpluses)	Not addressed	Directly quantified
Environmental impacts	Not addressed	Directly quantified
Regulated electricity tariff impacts	Not addressed	Directly quantified
Regulation fairness	Not assessed in detail	Assessed in detail
DG self-consumption[a]	Not addressed	Directly quantified
DG operational cost impacts	Three scenarios with arbitrary impacts	Directly quantified
DG energy loss impacts	Three scenarios with arbitrary impacts	Directly quantified
PEI calculation [b]	Not conducted	Conducted

[a] DG self-consumption influences the results considerably, since it is not subject to regulatory changes.
[b] Index on socioeconomic welfare created by the electricity market.

The main objective of the new regulatory policy is to decrease compensation for electricity injected into the grid to prevent DG deployment from harming any market players. If net metering were maintained, significant tariff increases would occur over time to avoid concessionaire bankruptcy. Thus, DG deployment could harm conventional consumers, and social inequality could increase. By implementing the new regulatory policy, more steady tariffs can be maintained over time, resulting in fairer policies, especially for consumers who cannot invest in DG systems. While implementing fairer policies and decreasing social inequality is legitimate, regulatory issues concerning DG influence several other topics e.g., the environment. Therefore, this paper seeks to assess the new regulatory policy's impact from a holistic and unbiased perspective. We also assessed mitigating tariff increases over time, which is the new policy's main goal. It is important to mention that Brazilian legislators want to mitigate tariff increases without eradicating the DG supply chain, i.e., they are seeking a middle ground. This trade-off is also addressed in this paper.

Several questions/concerns naturally arise in the context of regulatory changes for two main reasons:

(i) Proposing fair market regulations is not a trivial task; and
(ii) Regulatory changes massively impact society.

Therefore, before regulatory changes are implemented, it is extremely important to assess these two issues. More specifically, an in-depth analysis of the electricity market itself is required, along with using predictive models to assess the future implications of regulatory changes. Furthermore, a holistic view is also needed accounting for economic, social, environmental, political, and technical aspects.

The subject of this paper may be of global interest since regulatory DG changes are commonly applied. For example, recent regulatory framework changes have been passed in the USA, Germany, the UK, and Australia (NREL, 2017). The objectives of these changes are similar to Brazil's objectives i.e., reducing incentives as installed capacities become more substantial e.g., decreasing feed-in-tariff (FIT) rates in Germany (NREL, 2017). This paper fits well within the global context and could aid policymakers/regulatory agencies and researchers.

We assessed the impact of Ordinary Law (OL) 14300/2022 on DG businesses, market player surpluses, regulated tariffs, environment, and socioeconomic market welfare. This paper is relevant insofar as ANEEL stated that it could not quantify regulatory impacts on DG businesses and the environment (ANEEL, 2019b). Thus, the regulatory agency could greatly benefit from our proposed methodology and results.

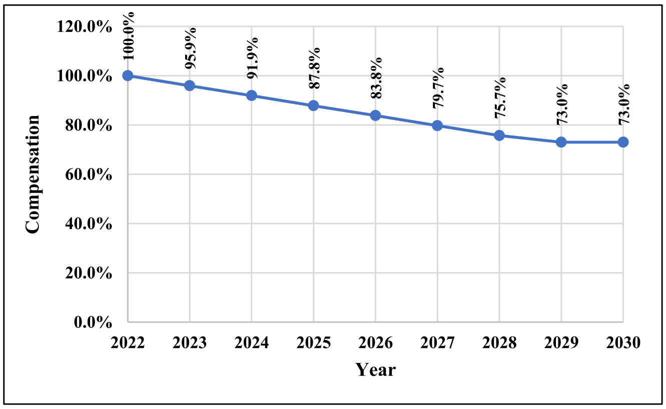

Fig. 1. OL compensation, adapted from the Brazilian House of Representatives (2019).

The optimized tariff (TAROT) model has been applied in several contexts to model regulated electricity markets. Publications include electricity market risk assessments (Cortez et al., 2018), power quality influences on markets (Arango et al., 2018), electricity theft effects (Arango et al., 2017), COVID-19 pandemic impacts (V. B. F. Costa et al., 2021b), (Costa et al., 2022) and fair social tariffs (Macieldos et al., 2020). The TAROT model is already well-established for regulated electricity market models, and the model's basic terms do not need to be modified. However, a literature review showed that these studies usually focus on specific topics, whereas holistic assessments are typically not conducted. This is clear since no cited publication directly addressed environmental aspects.

Regarding this paper's context, Costa et al. (2019), published a similar article. The authors analyzed older regulatory DG frameworks for ANEEL in 2019 (Public Hearing (PH) 25/2019), based on the TAROT model, which were not approved. This paper, however, proposes major approach modifications and improvements to this study, as highlighted in Table 1. Therefore, this study will provide an original view on the effects of new regulation offering a more rigorous/holistic analysis, increased accuracy, and better detailing of the results and their interpretation, in addition to assessing a regulatory framework that was approved by Congress (OL). We should also emphasize that the aforementioned study applied the TAROT model alone. By contrast, we will apply three models/methodologies together, i.e., the TAROT model, the Bass diffusion model (BDM), and life cycle assessment (LCA).

de Doyle et al. (2021), and de Oliveira Pinto Coelho et al. (2021), also assessed the OL. Their approach, however, was different from the approach taken in this paper, since they focused on the financial impacts of regulations on prosumers using Monte Carlo simulations. Moreover, the authors conducted time-independent analyses.

Meaningful works that address DG regulatory issues in Brazil include Andrade et al. (2020). The authors discussed how regulations might impact DG development and use. They did not address OL in detail, but did provide valuable debates on the role of regulation on multiple topics. Vazquez and Hallack (2018), developed an analytical framework to analyze DG deployment barriers. Dranka and Ferreira (2020), provided an up-to-date assessment of smart grid development, including DG policy trends, demand-side management, and new tariff regimes. Carstensdos and Cunha (2019), investigated photovoltaic (PV) generation from a socio-technical perspective. Although these works are important, we verified that in general, they offered empirical evaluations, i.e., there was a lack of analytical models for assessing regulatory changes, especially holistic models.

Our model is, however, similar to a model applied by V. Costa et al. (2021a). There are, nonetheless, big differences since the authors did not address OL. Furthermore, they focused on energy storage systems (ESS) and time-of-use (TOU) rates. They assessed future market conditions for Brazil, whereas our study addressed imminent short-term regulation changes in Brazil. Moreover, they did not offer a holistic assessment e.g., environmental and tariff aspects were not addressed. Furthermore, they addressed only one concession area, while 35 were analyzed here.

BDM is widely used for modeling demand for new technologies (Barkoczia et al., 2017b), (Bass, 2004), (Jung and Lim, 2016). DG is one application example, since regulatory agencies/government institutions worldwide have applied this model to forecast installed DG capacities. BDM studies forecasting installed DG capacities have been carried out by ANEEL (ANEEL, 2017), the National Renewable Energy Laboratory (NREL) (NREL, 2009), and academic researchers (Dong et al., 2017).

LCA is used to quantify environmental impacts i.e., environmental benefits or detriments, along the entire product life cycle. Furthermore, environmental DG performance has been evaluated using LCA (Antonanzas et al., 2019; Constantino et al., 2018; D.O.Akinyelea, R.K. Rayudua, 2017; Dones and Frischknecht, 1998; Eskew et al., 2018; Fu et al., 2015; Gazbour et al., 2018; Luo et al., 2018; Pacca et al., 2007; Peng et al., 2013; Perez and Fthenakis, 2011; Santoyo-Castelazo et al., 2021; Sherwani et al., 2010; Sumper et al., 2011; Zhai and Williams, 2010). However, LCA is usually applied independently i.e., authors conduct LCA without connecting other decision-making parameters, further highlighting the contributions of our study.

We must emphasize that applying the TAROT model, BDM, and LCA together will aid us in achieving our goals of assessing OL from a holistic point of view. More specifically, the TAROT method was used, since it is a regulated electricity market model that can quantify concessionaire surplus/profit, market socioeconomic welfare, and electricity tariffs. These three factors are thoroughly evaluated in our case study. The TAROT model was key in doing this. However, the TAROT model itself cannot conduct time-series analyses, quantify regulatory impacts on the DG system demand, nor quantify environmental impacts, which are also very important issues addressed in this study. Therefore, BDM is applied to enable time-series analyses by forecasting DG-generated electricity over time in each concession area. Moreover, BDM also quantifies regulatory impacts on the DG system demands. LCA was applied to analyze environmental impacts, since environmental issues are neither addressed by TAROT nor BDM. The literature review shows the novelty of environmental evaluations as presented here in this paper. In conclusion, jointly applying three methods is very important for conducting holistic time-series analyses in light of new regulations.

To offer context on the current state of DG in Brazil, which is the theme of this study, Section 2 (methodology) describes OL (Section 2.1). Sections 2.2, 2.3, 2.4, and 2.5 present the BDM, TAROT models, the LCA, and our proposed algorithm, respectively. Section 3 details the case study, which was conducted in detail for a concession area located in São Paulo state, Brazil (Section 3.1). Furthermore, Section 3.2. gives a thorough assessment dedicated to summarizing OL impacts on 35 Brazilian concession areas. For simplicity's sake, the model parameters are shown in the supplementary material (Costa, 2022).

2. Methodology

The methodology used in this paper was adapted for Brazil to assess OL. Similar ideas can be applied to other countries. However, adaptations to the TAROT model might be required, since country tariff regimes may change (Reneses et al., 2013), depending on government policies e.g., climate policies, or tax frameworks, for instance. Therefore, one may need to adapt the methodology in function of differing tariff regimes.

2.1. Ordinary Law (OL) 14300

OL was approved by the Brazilian Congress in Jan/2022. It decreases compensation over time, as shown in Fig. 1. The main goal was to maintain 100% compensation (net metering) until December 2045 for anyone who already has a DG system, along with all who request access

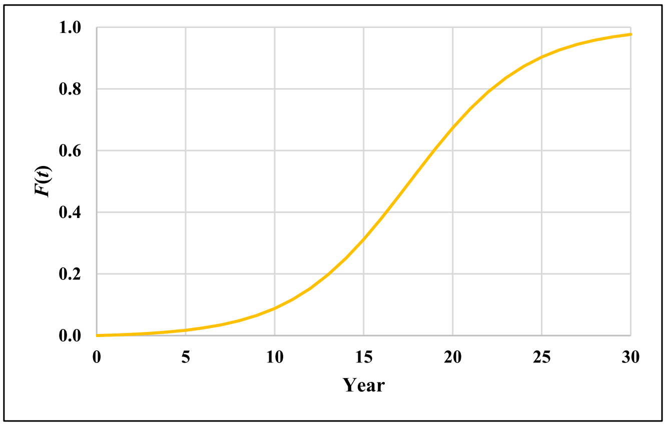

Fig. 2. Typical cumulative probability distribution function (adapted from (V. Costa et al., 2021a)).

from utility companies within one year after the law's implementation (until Jan/2023). This is why net metering is the current BAU for DG in Brazil. However, the OL states that if prosumers install DG systems one year after the law's implementation, compensation levels will decrease according to Fig. 1, i.e., the prosumer is not protected from regulatory changes. After 2030, the National Council for Energy Policies (CNPE) will define the compensation rules by calculating all DG costs and benefits, including generation, transmission, distribution, and energy loss improvements. ANEEL must publish rules by Jun/2023. We should emphasize that the OL is valid for all renewable DG sources, although PV dominates market shares at more than 99% of all DG connections (ANEEL, 2021a).

There are other aspects related to the OL e.g., reducing legal risks associated with DG integrations. However, these issues fall outside the scope of this study, since they are not related to prosumer compensation.

This paper focuses on the OL, since this was the regulatory framework approved by the Brazilian Congress. Nevertheless, the PH simulation results for alternative 5 (ANEEL's regulatory proposal (ANEEL, 2019b)), were also included in the graphs and tables for **comparison's sake** in the conclusions section. The PH was proposed in 2019 by ANEEL but was not approved. Although the PH featured five alternatives, alternative 5 was included since it was the most different from the OL. Furthermore, a similar regime (relatively low compensation) might be implemented in 2030. It suggests 43% constant compensation over the years.

As mentioned above, we carried out a holistic assessment based on the BDM, TAROT, and LCA methods which are described as follows.

2.2. *The Bass diffusion model*

The BDM forecasts technology demands (DG) as expressed in Equation (1) (Barkoczia et al., 2017b), (Bass, 2004), (Jung and Lim, 2016):

$$F(t) = \frac{1 - e^{-(p_B + q_B)t}}{1 + \frac{q_B}{p_B} e^{-(p_B + q_B)t}} \tag{1}$$

where:

$F(t)$ is the BDM cumulative demand distribution function;

p_B is the innovation parameter;

q_B is the imitation parameter;

t is time.

Parameters p_B and q_B dictate the exact shape of the demand curve (how fast it increases/settles), and must be defined based on historical data.

In this paper, we assumed an annual time step since we wanted to determine the long-term effects of the OL's impact.

The shape of (1) is given in Fig. 2. (general example for any technology). One can see that the shape is similar to an S-curve, i.e., the curve increases slightly in the beginning, given technology purchase delays. By contrast, the rate of increase is substantial in the medium term, since technology popularity extends. Finally, the rate of change slows down over the long term for two reasons:

(*i*) Most potential buyers already purchased the technology; and
(*ii*) The technology might become obsolete/outdated.

The maximum value of (1) is one, since it is a cumulative distribution function. Equation (2) must be applied to estimate the actual generated electricity from DG systems ($E_G(t)$):

$$E_G(t) = E_G(t-1) + m_p m_{mf}[F(t) - F(t-1)] \tag{2}$$

where:

$F(t)$ is the cumulative distribution function obtained from (1);

m_p is the market potential (maximum theoretical electricity generation).

This paper applies a similar approach to (ANEEL, 2017a) to estimate m_p, as shown in Appendix A. One can also forecast DG installed capacity provided that m_p is properly estimated (m_p depends on the quantity of interest); m_{mf} is the maximum market fraction, expressed by:

$$m_{mf} = e^{-P_{BS} P_{BT}} \tag{3}$$

where:

m_{mf} is given in %;

P_{BS} is the payback sensibility;

P_{BT} is the payback time.

The major advantage of BDM relative to other forecasting techniques is that it considers the payback time within the model, i.e., it can quantify OL impacts on DG system demand, which is very important for fulfilling this paper's objective. More specifically, the OL leads to higher P_{BT} and consequently decreases DG system demand.

Naturally, installed DG systems do not depend on current P_{BT}, i.e., only new prosumers are subject to the OL when deciding to purchase a DG system or not. Since P_{BT} might vary over time given compensation changes, segregation between time steps t and $t-1$ is required in (2). The initial generated electricity from DG (generated electricity in the first time step) was obtained from historical data (ANEEL, 2021a).

Here we assumed that wealthier regions are more susceptible to DG integrations, to increase the model's accuracy, as per (4):

$$P_{BS} = P_{BS(M)} - \frac{\ln A_I}{P_{BT}} \tag{4}$$

where:

m_{mf} is taken as a proportion of average incomes, equivalent to assuming that DG demand is proportional to average income (mathematical proof provided in Appendix A).

$P_{BS(M)}$ is the mean payback sensibility of the country, estimated at 0.4 by (ANEEL, 2017).

A_I is the average income in per unit.

Consequently, four factors influence the BDM estimation:

(i) Average regional income (modeled using P_{BS});
(ii) Market size (modeled through m_p);
(iii) Economic feasibility of investing in DG systems (modeled using P_{BT}); and
(iv) Historical DG integration data (modeled using p_B and q_B) (V. Costa et al., 2021a).

2.3. *Optimized tariff model*

This section summarizes the most important aspects of the TAROT model, since this methodology has been widely addressed in literature

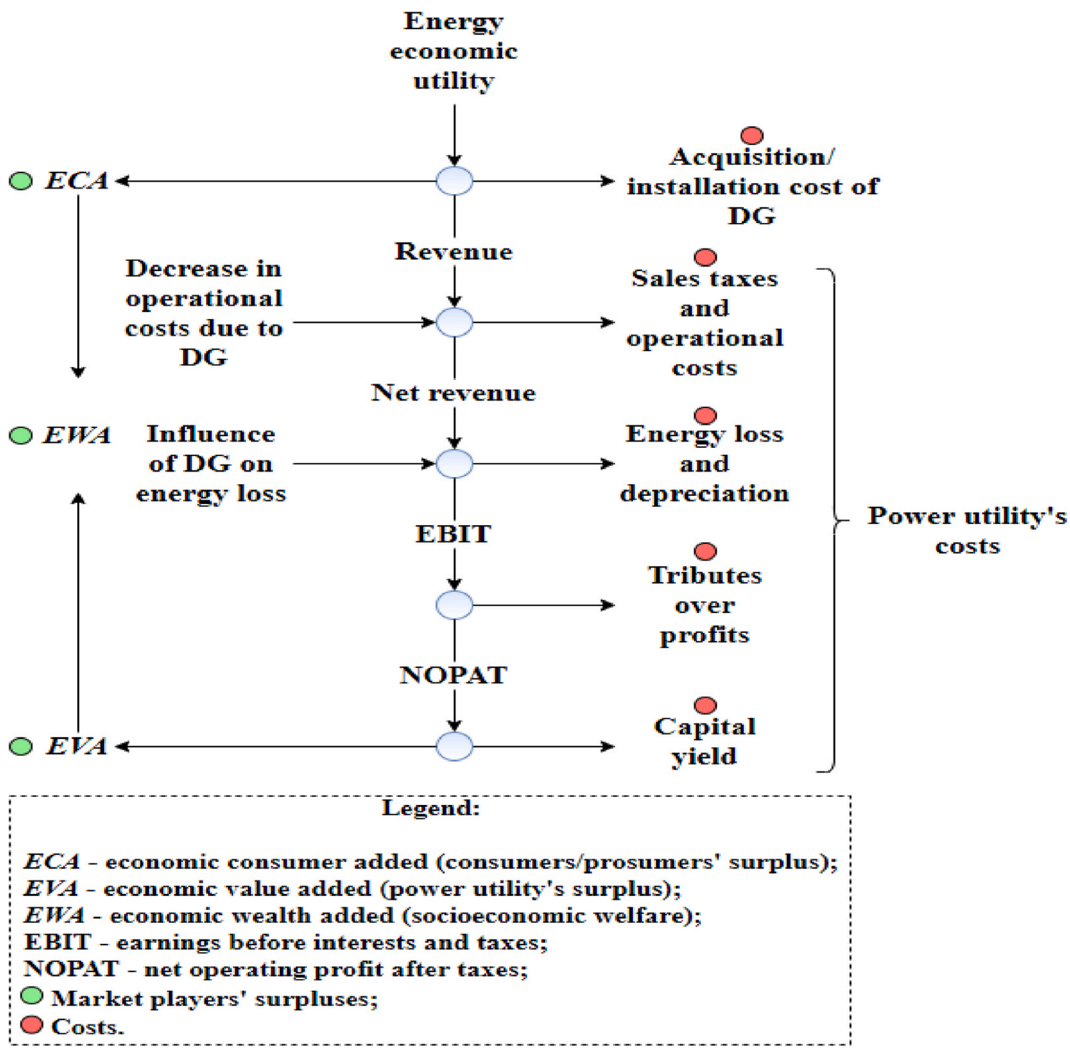

Fig. 3. Block diagram of economic flows in a regulated electricity market (adapted from (Costa et al., 2019)).

(Arango et al., 2018, 2017; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b). Naturally, changes to improvement approaches relative to Costa et al. (2019), have been made, since this study was most similar to our study.

This study addresses the OL parameters that are significantly time-varying influencing to assess impacts over time, i.e., DG generated electricity, prosumer compensation, regulated tariffs, and electricity consumption. However, the time function notation (t) has been omitted for simplicity's sake.

The TAROT model equations are primarily based on economic flow block diagrams, as shown in Fig. 3. The green circles are market player surpluses, i.e., each agent's benefit from economic transactions (electricity purchases/sales). By contrast, the red circles are inherent to electricity distribution costs.

The model is usually separated into three parts for better organization i.e., the consumer/prosumer model, the regulated distribution company model, and the overall socioeconomic model.

2.3.1. *The consumer/prosumer model*

The consumers/prosumer surplus (economic consumer added (ECA)), i.e., the consumers/prosumer benefits from economic transactions, is given by:

$$ECA = U - R - C_D \tag{5}$$

where:

$U = aE - (b/2)E^2$ is the economic utility function, measuring the additional quality of life in function of electricity consumption. This allows TAROT to be used as a socioeconomic model for consumer/prosumer electricity, rather than merely an economic model;

a is the avidity parameter, i.e., willingness to consume electricity;

b is the satiety parameter, i.e., the degree of satisfaction with the consumed electricity; and.

E is the consumed electricity;

$R = T\{E - E_G[l + (1-l)n]\}$ is revenue, i.e., amounts paid to concessionaires from electricity sales. Where:

T is the regulated electricity tariff;

E_G is the overall DG-generated electricity. Here, future E_G values are forecasted based on the BDM (Equation (2));

l is the share of self-consumption of DG-generated electricity from DG in (%);

$(1-l)$ is the share of DG-generated electricity injected into the grid; and.

n is the compensation parameter for on-grid DG in (%), i.e., the parameter that models OL in the TAROT model (values indicated in Fig. 1).

In conclusion, the OL is represented in the TAROT model via n, represented by payback time (P_{BT}) as per (3), in the BDM.

$C_D = s_1 E_G$ models DG-prosumer acquisition/operational system costs (capital expenditures (CAPEX) and operational expenditures (OPEX));

s_1 is the cost parameter for the DG system CAPEX and OPEX.

Compensation decreases in (5) only for prosumers who install DG systems after Jan/2023 (as stipulated by law).

(Costa et al., 2019) did not define l, i.e., they did not consider generated DG electricity separation into two components (both self-consumed and injected electricity into the grid). More specifically, they took all generated electricity as being injected into the grid, which negatively affects the results considerably, since self-consumption is not subject to regulatory changes, i.e., self-consumption is independent of n.

Consumers/prosumers naturally seek to adjust their electricity consumption to maximize benefits. Therefore, Equation (6) must be satisfied:

$$\frac{\partial ECA}{\partial E} = 0 \Rightarrow T = a - bE \tag{6}$$

Based on Equation (6), the TAROT model can quantify electricity consumption variations in function of tariff variations. Therefore, demand responses (DR) are accounted for. Electricity consumption variations influence other terms in the TAROT model that depend on E.

2.3.2. Regulated distribution company model

The regulated distribution company surplus (economic value added (EVA)), i.e., the company's benefit from engaging in economic transactions, is given in:

$$EVA = R - C \Rightarrow EVA = (1-t)\left\{ R - \left[\left[eE - e' E_G + \frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{B} + \mu R + Bk \right] \right] \right\} \tag{7}$$

where:

R, E, E_G are defined in (5);

C are concessionaire costs;

t are taxes on profits;

e are operational costs (operational costs include: sector charges, transmission costs, electricity purchase costs, administration, operation, and maintenance (O&M) costs, and mobile and real estate infrastructure costs);

e' models decreases in operational costs in function of DG;

p is the energy loss cost for null DG penetration;

f and g model DG influence on energy loss costs;

B is the grid investment;

μ is sales tax;

k is the hurdle rate for concessionaire value aggregation. It depends on both grid depreciation and capital yields.

In this paper, both operational costs ($eE - e'E_G$) and energy loss costs $[f(E_G/E)^2 + g(E_G/E) + pE^2]/B$ were calculated differently from Costa et al. (2019), using more valid/accurate methods. These terms are discussed in more detail.

To accurately estimate the operational costs, one needs to analyze the operational costs that are significantly influenced by DG. Both transmission costs and electricity purchase costs are significantly influenced by DG since:

(i) Transmission is mostly unnecessary for electricity supplied from DG systems; and
(ii) DG decreases the amount of purchased electricity by the concessionaire.

DG might also influence O&M costs, however, it is not always clear how this occurs, since DG may be linked to increased procedural and maintenance complexity (Passey et al., 2011). Other categories, i.e., sector charges and costs related to mobile and real estate infrastructure, should not be significantly influenced by DG. Consequently, operational costs are modeled based on (8) and (9). Equation (8) is a traditional equation applied to obtain e in the TAROT model (Arango et al., 2018, 2017; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).

$$e = \frac{E_S + C_T + C_C + C_A + C_I}{E} \tag{8}$$

$$e' = \frac{C_T + C_C}{E} \tag{9}$$

where:

E_S are the sector charges;

C_T are the transmission costs;

C_C are the electricity purchase costs;

C_A are the O&M costs;

C_I are costs related to mobile and real estate infrastructure.

This approach ensures that the operational costs are correctly estimated rather than arbitrary. In practice, e' is in the order of 60% of e (in Brazil), meaning that DG is reasonably efficient in decreasing operational costs (it is important to note that $e'E_G$ subtracts the cost in (7)).

Energy loss costs must satisfy the physics of how DG influences energy losses, which was not the case in (Costa et al., 2019). It is commonly recognized that the influence of DG on energy losses is U-shaped (Ebrahimi et al., 2013; Karunarathne et al., 2021; MendezQuezada et al., 2006; Sheikhi et al., 2013; Singh and Parida, 2011). More specifically, DG tends to be beneficial for low/medium penetrations, since it reduces conventional system use that requires extensive electricity transmission. However, DG tends to increase energy losses for substantial penetrations, given reverse power flows (RPF). Consequently, energy losses are modeled via a concave upward-facing parabola $[f(E_G/E)^2 + g(E_G/E) + pE^2]/B$. Both f (positive parameter) and g (negative parameter) are obtained from power flow simulations, whereas p (the conventional energy loss parameter of the TAROT model) and B (grid investment of the TAROT model) are included to adapt the energy loss term to the TAROT model. Energy loss costs are taken as being proportional to energy losses, since concessionaires purchase electricity in the wholesale market using long-term contracts to supply captive consumers in Brazil (ANEEL, 2021b). Thus, price volatility is limited. Similar ideas for energy loss costs have been applied in (V. Costa et al., 2021a) to assess the electricity markets with ESS integrations.

The energy loss costs indirectly influence optimal grid investments B^*, i.e., grid investments that concessionaires need to minimize costs and maximize surplus:

$$B^* = \sqrt{\frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{k}} \tag{10}$$

Unless the penetration levels are substantial, the model quantifies DG investment deferrals, since the optimal grid investment from (10) is lower than the optimal grid investment without DG ($B^* = (\sqrt{p/k})E$). In summary, the following DG benefits are quantified within the model (besides investment deferrals) (V. Costa et al., 2021a):

- Reduced revenue or electricity bill (benefits for prosumers to the detriment of concessionaires);
- Reduced operational costs;
- Reduced energy loss costs (unless penetration levels are substantial);
- Reduced grid depreciation;
- Reduced taxes on profits;
- Reduced sales tax;
- Reduced capital yields.

2.3.3. Overall socioeconomic model

The socioeconomic welfare (economic wealth added (EWA)) is defined as the overall benefit to society from economic transactions (see Equation (11)).

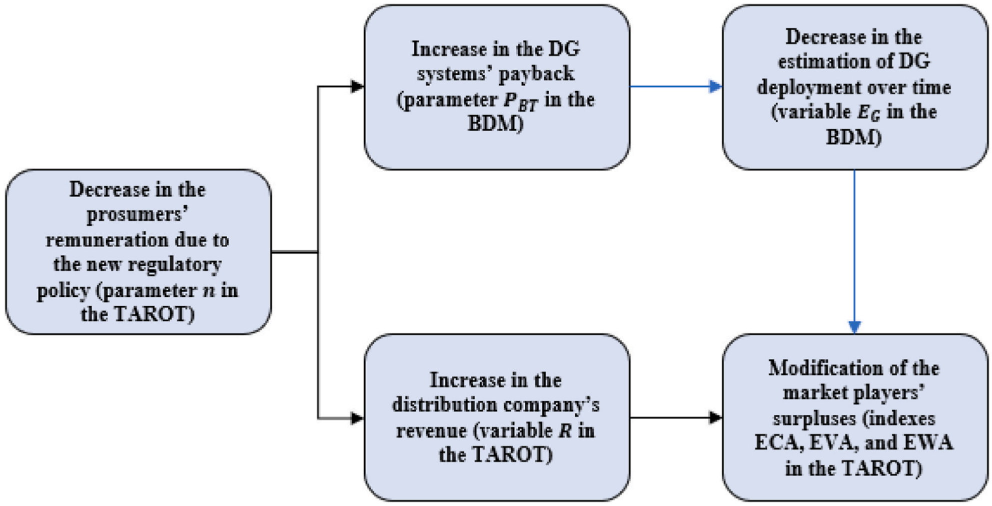

Fig. 4. Relationship between the TAROT model and the BDM.

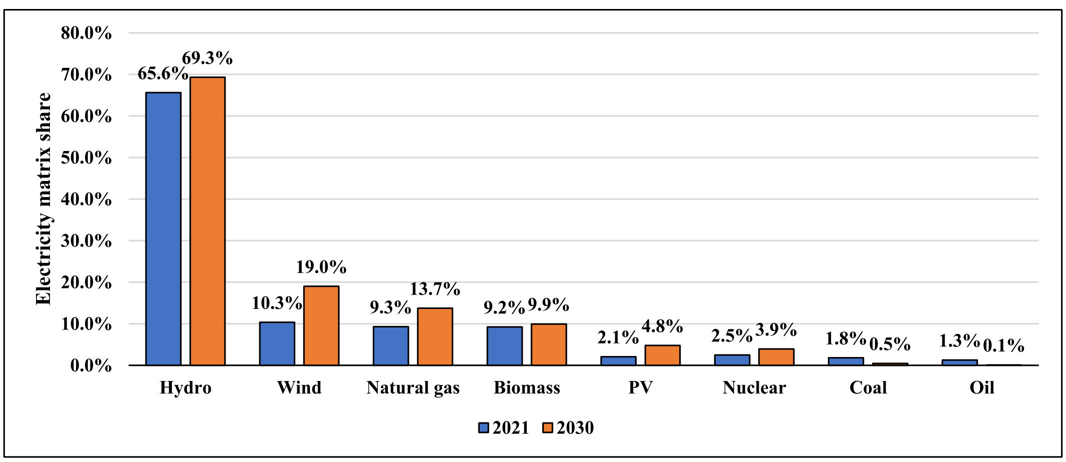

Fig. 5. Brazilian electricity matrix for quantifying the environmental impacts of conventional/centralized generation (adapted from (EPE, 2021a, 2021b)).

$$EWA = ECA + EVA \tag{11}$$

The regulatory agency's goal is to maximize EWA. However, it must also maintain market sustainability, i.e., avoid $EVA < 0$, and consequently, bankruptcy. In Brazil, ANEEL adopts (12) to maximize socio-economic welfare while guaranteeing market sustainability:

$$EVA = 0 \tag{12}$$

In other words, ANEEL applies (12) to calculate the tariff that can cover all company costs, thereby ensuring FEE for companies and maximum affordability for consumers/prosumers.

Fig. 4 shows the relationship between the TAROT model and the BDM. The black arrows deal with immediate implications. OL decreases n in the TAROT model, immediately increasing concessionaire revenue and modifying market player surpluses. The blue arrows deal with long-term implications. The OL decreases the BDM's estimation of DG deployment over time, which ultimately also influences market player surpluses. Therefore, the methodology quantifies both immediate and long-term effects of the OL, offering robust results.

2.4. Life cycle assessment

The LCA was carried out here based on the steps as suggested in ISO 14040 and 14044 (ISO, 2006).

2.4.1. Defining the goal and scope

As stated earlier, the OL inherently decreases DG system demand (or power capacity). Thus, the goal of the LCA as applied here was to quantify/forecast environmental impacts caused by demand reductions. All LCA considerations are described in Appendix B.

Global warming/climate change is typically among the most worrying environmental impact categories (Lorenzoni and Pidgeon, 2006). Consequently, this paper focuses on global warming potential (GWP). The Intergovernmental Panel on Climate Change (IPCC) 2013 life cycle impact assessment (LCIA) method was used here.

2.4.2. Life-cycle inventory

The cradle-to-gate LCI from the PV modules and inverters were obtained from (Yang et al., 2015) and (Treeze, 2016), respectively. By contrast, the transmission (imports and internal distribution) and usage phases were estimated based on Brazilian data. Regarding conventional/centralized generation, we used the Ecoinvent database 3.7.1 (Ecoinvent, 2020), since it has processes that represent the Brazilian electricity matrix. However, the electricity matrix available in this database dates back to 2014. It was updated to increase the accuracy of the LCA, as per Fig. 5. Moreover, electricity matrix variation over time was also accounted for, for enhanced accuracy. Given that only data from 2021 to 2030 were available, a linear variation for the electricity matrix was used. Lastly, the Ecoinvent database was also used for background processes.

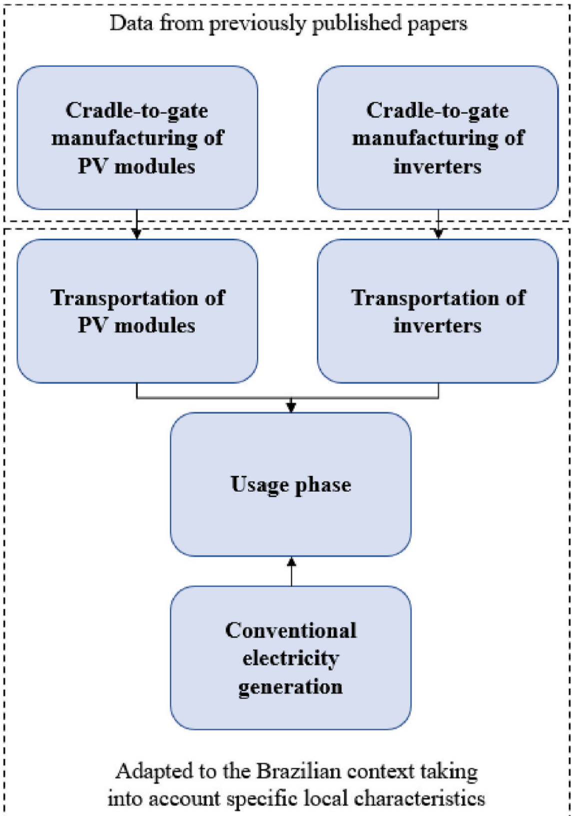

Fig. 6. Simplified product system boundaries.

A simplified product system is shown in Fig. 6. The cradle-to-gate processes were highly simplified in Fig. 6. In fact, the cradle-to-gate manufacturing for PV modules and inverters involves seven and five processes, respectively. Detailed information on these processes is available in (Treeze, 2016; Yang et al., 2015), more specifically, Table 3.2 in (Treeze, 2016) and Tables 2–7 in (Yang et al., 2015). Although Fig. 6 has been simplified, all processes were addressed in the simulations to ensure accurate results.

The processes adapted to Brazil naturally depend on particular local characteristics, more specifically, the amount of peak sun hours (PSH) and technology transportation requirements vary depending on location (Brazil is a very large country). The LCI for each concession area differs according to the amount of PSH and transportation requirements. The LCI of the processes adapted to Brazil was taken for the *CPFL Paulista* concession area, located in *São Paulo* state, since this was the main analyzed area in this case study (Tables B1-B2 in Appendix B). Nevertheless, the LCI for the other concession areas is available as supplementary material (Costa, 2022).

The LCA's stages 3 (LCIA) and 4 (interpretation) are jointly performed with the case study in Section 3.

2.5. Final concepts and proposed algorithm

This section presents two final concepts, i.e., the stopping criterion and the performance index. These concepts are required given the time-series approach. Both have already been defined in detail in (V. Costa et al., 2021a), so we will merely summarize their definition.

Stopping criterion: according to (V. Costa et al., 2021a), the stopping criterion is defined based on $F(t)$ from (1), since it is percentage-based. However, since 35 concession areas were analyzed in this study, this approach is not appealing, since it results in different simulation intervals for each concession area. Instead, our simulations were conducted until 2030 for all concession areas for three main reasons:

(i) In general, DG system integrations decrease significantly after 2030;
(ii) The OL does not specifically detail its compensation regime past 2030 (calculation procedure) (Brazilian House of Representatives, 2019); and
(iii) Electricity matrix data were not available past 2030.

Performance index (PEI): the PEI is defined based on market socioeconomic welfare (EWA):

$$PEI = -EWA(t_0) + \frac{1}{(t_1 - t_0)} \int_{t_0}^{t_1} EWA(t)dt \tag{13}$$

where:
t_0 is the initial simulation year;
t_1 is the final simulation year;
$EWA(t_0)$ is the market's initial EWA, subtracted so that PEI is expressed in terms of gains or variations.

The PEI defined in (13) corresponds to mean socioeconomic welfare gains from DG integrations. It is important in quantitatively/impartially assessing the consequences of the OL. Given that this study seeks to conduct holistic analyses, we should mention that PEI is not the only index/factor that was analyzed here. More specifically, PEI only considers EWA from the TAROT model and not from other factors like environmental aspects. While one can consider environmental aspects together with the EWA in (13), there seems to be no global consensus among experts as to how to value greenhouse gas (GHG) emissions in currency terms (Rubin et al., 2015). Therefore, quantifications are conducted separately to not negatively impact results.

The proposed OL holistic assessment algorithm is shown in Fig. 7.

3. Results

São Paulo was selected for analysis given its high economic development (the highest in Brazil), and installed DG capacity (second highest in Brazil) (ANEEL, 2021a). *São Paulo's* Gross Domestic Product (GDP) is 603 billion (USD), more than 40% of Brazil's entire GDP (Government, 2020). Electricity consumption in São Paulo is 132 (GWh) (EPE, 2020), accounting for more than 27% of Brazil's entire electricity consumption. DG installed capacity there is 1.3 (GW) (ANEEL, 2021a), more than 12% of Brazil's total installed DG capacity. *CPFL Paulista* is one of the main concessionaires in *São Paulo* and currently has significant installed DG capacity (ANEEL, 2021a, 2021b), thus, why we chose to study this concession area.

Appendix A gives information on how to obtain the parameters and shows the *CPFL Paulista* values. The parameters values for other concession areas are also given as supporting material (Costa, 2022). All input parameters were based on PV DG systems (BDM, TAROT, and LCI), and since PV DG systems constitute more than 99% of all DG connections in Brazil (ANEEL, 2021a), the results will provide a proper overview of the OL impacts.

3.1. Case study - CPFL Paulista

3.1.1. Distributed generation business

This section focuses on applying the BDM to verify the OL influences on DG businesses. The TAROT model and the LCA were not yet considered. More specifically, the TAROT was not considered since it only models the electricity market (not DG businesses).

Fig. 8 *a*) shows the OL impacts on generated DG electricity and on installed capacity over time. The impacts are significant (approximately 0.64 (TWh/year) in the long term).

Table 2 gives an estimate of the OL impacts on DG business based on

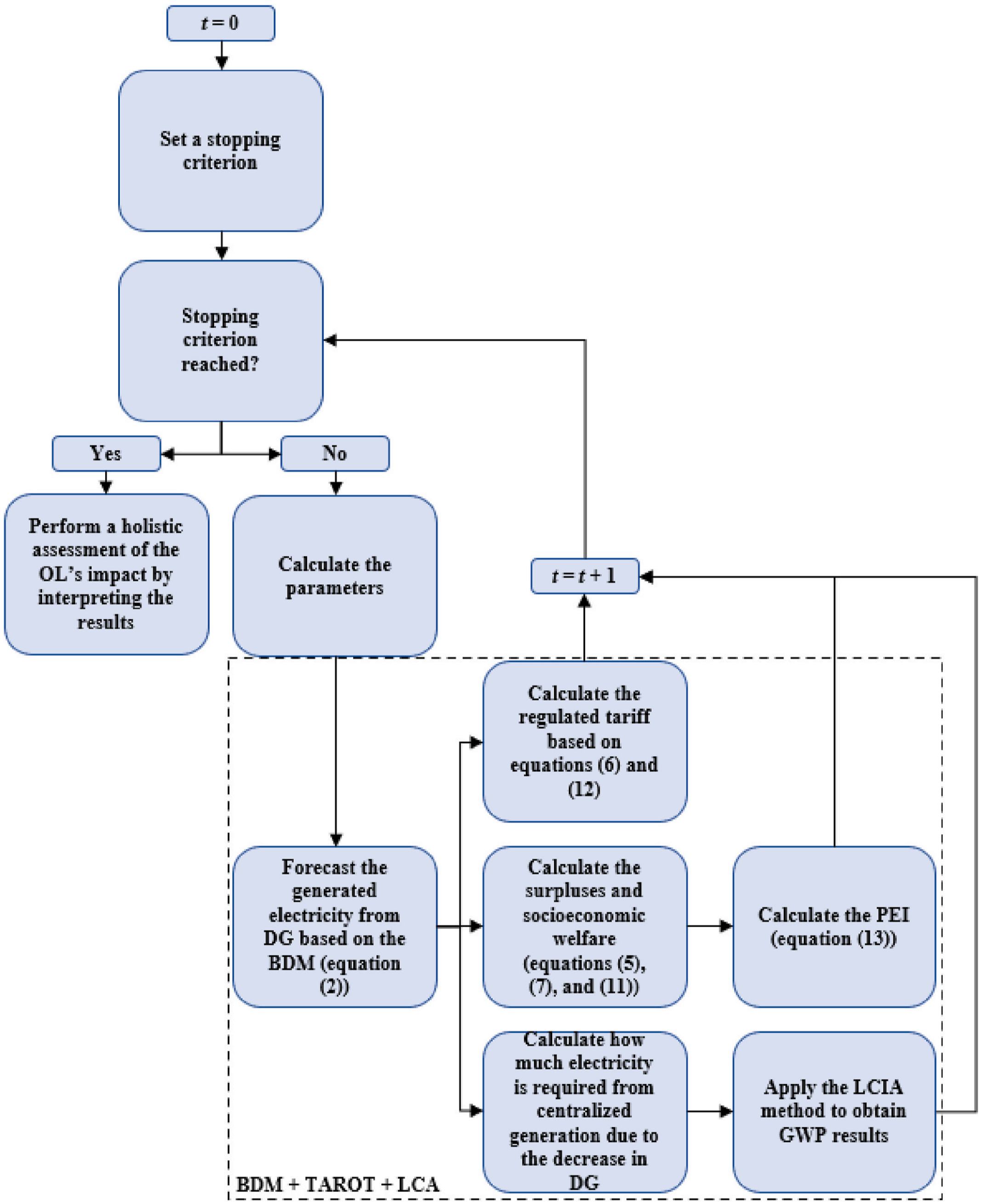

Fig. 7. Proposed algorithm.

data from (BlueSol, 2021) (Greener, 2021). 1 (MBRL) corresponds to 1 million (BRL) or 199 thousand (USD). The estimations assume that impacts are proportional to generation, or the capacity difference between net metering and the OL. Regarding employment issues, jobs among all productive links in the sector are accounted for. Furthermore, the results are based on a long-term assessment (2030). The OL impacts are estimated at 10.5%, and should, therefore, not be disregarded.

3.1.2. Market player surpluses and performance index

This section analyzes the OL impacts on market player surpluses, and on the PEI, assuming constant tariffs (Table A1). While regulated tariffs are expected to vary over time given ANEEL's tariff review processes, we need to verify the OL impacts in the absence of external regulatory interventions. The results can be interpreted as a natural trend for the electricity market.

Fig. 8 *b*) shows the OL impacts on concessionaire surpluses. Some critical phenomena are observed:

(i) DG integration significantly decreases EVA for net metering policy and for the OL. However, the decrease for the OL was less pronounced;
(ii) The net metering policy results in negative EVA after 2026; and
(iii) The oscillation of the OL curve is due to variable compensation over time, implying changes in company revenue. The oscillation phenomenon will also be observed in other graphs.

Fig. 8 *b*) shows that concessionaire profits or surpluses (EVA) decrease. As discussed in Section 1, this is because decreased company revenue is more influential, although DG does decrease several costs e.g., grid costs, energy losses, and operational costs. The OL would be acceptable from the concessionaire's point of view over the long-term, since it does result in $EVA > 0$ in the simulations. Therefore, the

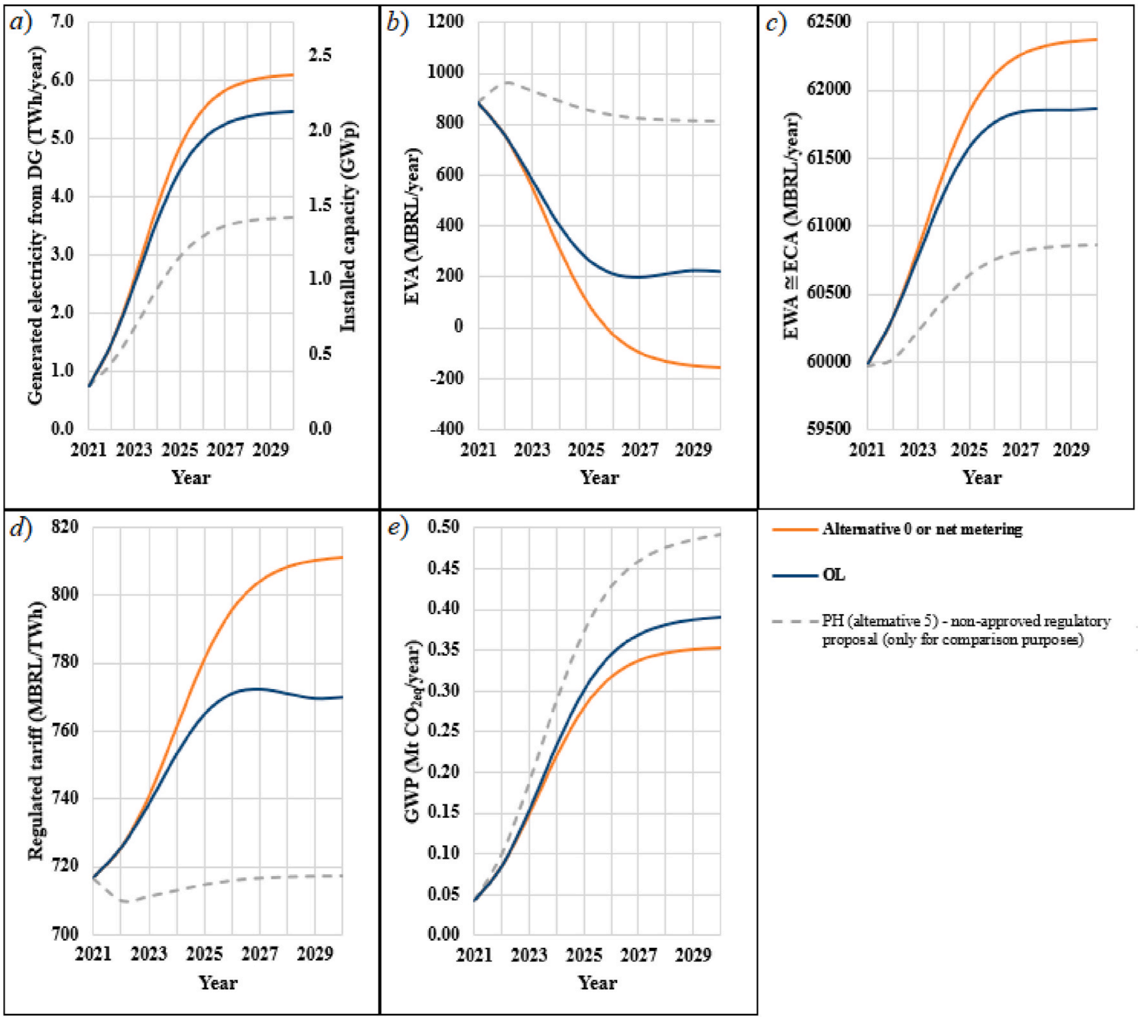

Fig. 8. OL impact on *CPFL Paulista* in terms of *a*) generated DG electricity, *b*) EVA, *c*) EWA, *d*) regulated tariffs, and *e*) GWP.

Table 2
Estimated OL impacts on DG businesses (*CPFL Paulista* – year 2030).

Policy	DG systems' sales (MBRL/ year)	Employment (number of people)	Impact in (%)
Alternative 0 or net metering	**910.1**	**196,076**	–
OL	**814.2**	**175,419**	**10.5**
PH (alternative 5) – non-approved regulatory proposal (only for comparison purposes)	545.9	117,626	40.0

Table 3
Estimated OL impacts on the PEI (*CPFL Paulista* – year 2030).

Policy	PEI (MBRL)	PEI reduction (MBRL)	Impact in (%)
Alternative 0 or net metering	**1646.4**	–	–
OL	**1375.6**	**270.8**	**16.4**
PH (alternative 5) – non-approved regulatory proposal (only for comparison purposes)	583.6	1062.8	64.6

company would be able to pay all its costs and operate sustainably. By contrast, net metering would result in concessionaire bankruptcy over the long term since $EVA < 0$. It is emphasized, however, that the net

Table 4
Estimated OL impacts on GWP (*CPFL Paulista* - year 2030).

Policy	GWP (Mt CO_{2eq}/ year)	Impact in (Mt CO_{2eq}/year)	Impact in (%)
Alternative 0 or net metering	**0.353**	–	–
OL	**0.390**	**0.037**	**10.4**
PH (alternative 5) – non-approved regulatory proposal (only for comparison purposes)	0.493	0.140	39.6

metering policy is only critical from the company's point of view in the long term (past 2026, according to the simulations).

Fig. 8 *c*) shows the OL impacts on market socioeconomic welfare. The consumers/prosumers surpluses are relatively close to the EWA. From a practical standpoint, Fig. 8 *c*) can also be interpreted as ECA. DG integration substantially increases EWA under net metering, and under the OL, although the latter results in a lower EWA. Additionally, the EWA for the OL is practically constant towards the end of the simulation period, since there is less DG integration (Fig. 8 *a*)), while compensation continues to decrease.

Table 3 compares the PEI of the policies. PEI impacts are also significant.

3.1.3. Regulated tariffs and social inequality

In this section we study the OL effects on regulated tariffs. Equations

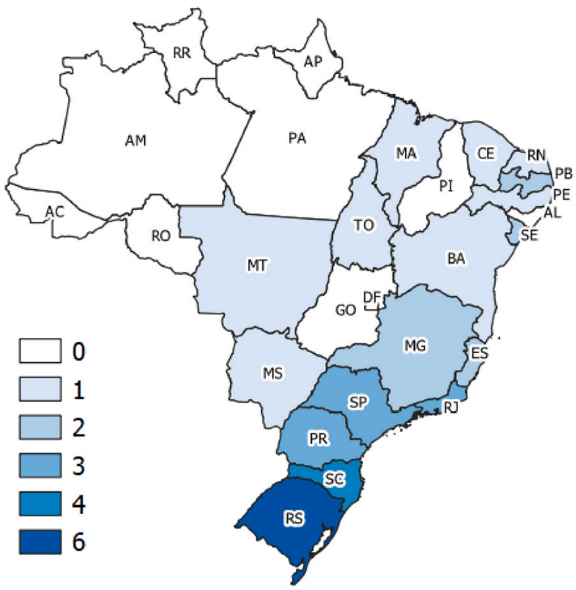

Fig. 9. Map of the analyzed concession areas.

(6) and (12) were applied annually (a numerical solution is required since there is no analytical solution). ANEEL conducts a similar procedure in practice, and so this methodology is broadly applied in Brazil.

We should emphasize that the analyzed company would have $EVA >$ 0 until 2026 for net metering, as per Fig. 8 *b*). Therefore, immediate tariff modifications are not needed to prevent bankruptcy. However, in this section, the tariff was calculated using $EVA = 0$ throughout the simulation period (Equation (12)), for more solid conclusions on OL impacts.

Fig. 8 *d*) shows that DG integration increases tariffs notably for net metering in the long term. This is due to decreased EVA tendencies, as per Fig. 8 *b*). The OL decreases tariffs significantly compared to net metering, however, only in the medium/long term, i.e., when compensation reduces considerably.

This section demonstrates that OL decreases social inequality relative to net metering, since the former partially mitigates tariff growth induced by DG integration.

3.1.4. The environment

The OpenLCA software program was used to assess OL effects on climate change. All results were based on GWP 100a (over 100 years).

Fig. 8 *e*) gives a GWP comparison, and there is a considerable difference in the GWP due to higher GWP for conventional/centralized generation compared to PV DG generation. The results show that conventional/centralized generation is currently 78% more hazardous, in terms of GWP, in the *CPFL Paulista* concession area, even though Brazil is known for having a renewable electricity matrix mainly comprising hydroelectric power plants (66%). The GWP of PV DG is estimated at 57.95 (g CO_{2eq}/kWh) for *CPFL Paulista*, while conventional/centralized generation GWP is estimated at 102.92 (g CO_{2eq}/kWh) for 2021, and 115.30 (g CO_{2eq}/kWh) for 2030. The increase over time for centralized generation is due to natural gas growth, which proved to be more

Table 5
Description of the analyzed concession areas.

Concession area	State	Electricity consumption (TWh/year) (ANEEL, 2021b) [a]	Generation from DG (TWh/year) (ANEEL, 2021a) [b]	Regulated tariff (MBRL/TWh) (ANEEL, 2021b) [a]	Average monthly income per family (MBRL) (IBGE, 2022) [c]
COELBA	BA	19.64	0.444	806.7	965
ENEL CE	CE	12.14	0.450	601.5	1028
EDP ES	ES	7.40	0.170	768.9	1347
ELFSM	ES	0.55	0.020	836.1	1347
CEMAR	MA	7.58	0.240	620.7	676
CEMIG-D	MG	31.43	2.149	739.1	1314
ENERGISA MG	MG	1.38	0.097	846.6	1314
ENERGISA MS	MS	5.48	0.342	740.7	1488
ENERGISA MT	MT	9.40	0.871	1013.7	1401
ENERGISA BO	PB	0.62	0.030	603.3	892
ENERGISA PB	PB	4.49	0.204	689.7	892
CELPE	PE	13.94	0.396	595.4	897
COCEL	PR	0.21	0.003	814.8	1508
COPEL-DIS	PR	22.67	0.529	722.4	1508
FORCEL	PR	0.04	0.003	917.7	1508
ENEL RJ	RJ	11.18	0.278	889.4	1723
ENERGISA NF	RJ	0.32	0.004	875.7	1723
LIGHT	RJ	25.26	0.149	720.7	1723
COSERN	RN	5.34	0.290	746.3	1077
DEMEI	RS	0.15	0.006	736.3	1759
ELETROCAR	RS	0.18	0.013	784.5	1759
HIDROPAN	RS	0.09	0.006	863.6	1759
MUX ENERGIA	RS	0.07	0.002	684.8	1759
RGE SUL	RS	16.78	0.983	751.5	1759
UHENPAL	RS	0.09	0.003	688.1	1759
CELESC-DIS	SC	18.34	0.250	707.1	1632
COPERALIANÇA	SC	0.21	0.002	644.0	1632
EFLJC	SC	0.02	0.000	721.2	1632
EFLUL	SC	0.04	0.002	1101.6	1632
ENERGISA SE	SE	3.16	0.069	671.8	1028
SULGIPE	SE	0.35	0.004	636.9	1028
CPFL Paulista	SP	23.59	0.685	793.4	1814
AES Eletropaulo	SP	35.80	0.068	667.4	1814
ELEKTRO	SP	12.75	0.357	745.5	1814
ENERGISA TO	TO	2.59	0.125	787.7	1060

[a] Reference year 2020/2021.
[b] Reference year 2021.
[c] Data by state.

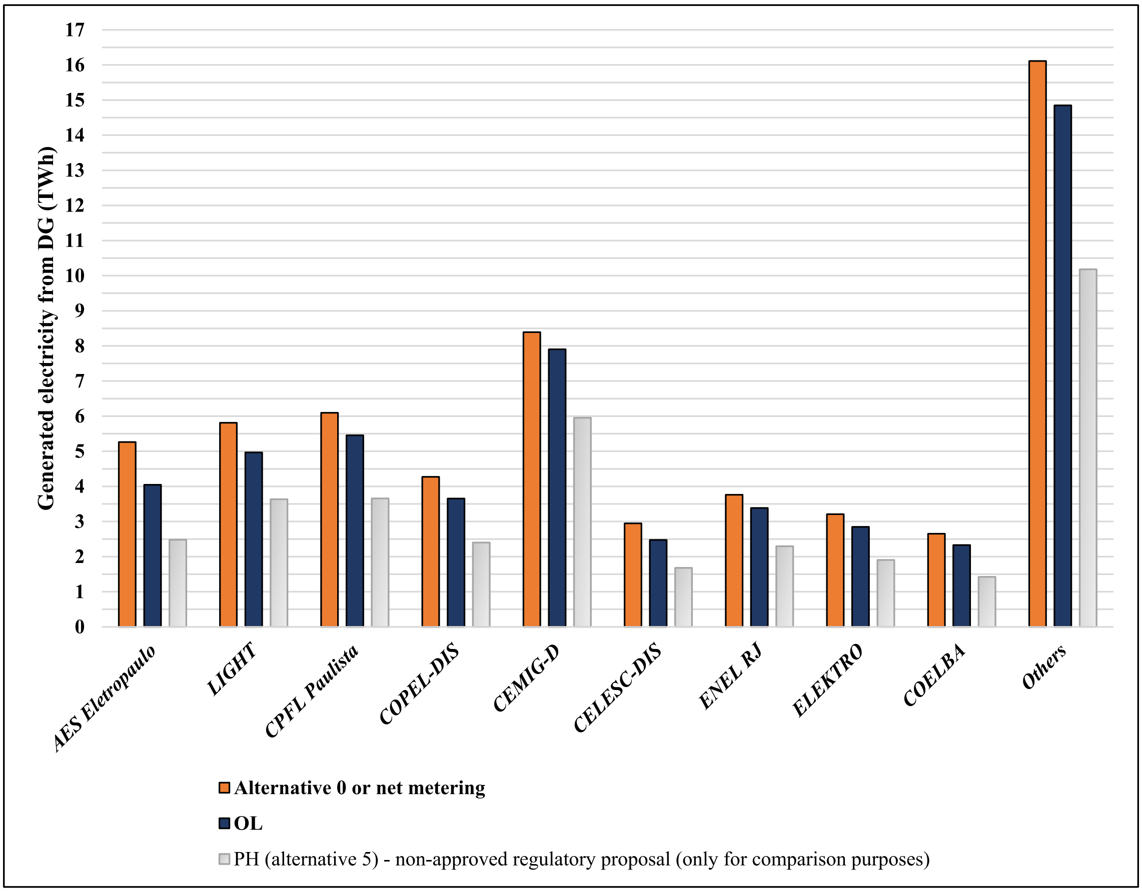

Fig. 10. Ranking the most affected concession areas in terms of the generated DG electricity in (TWh) for 2030.

influential than declining coal and oil use. It is important to note that Fig. 8 *e*) tapers off less intensely than in Fig. 8 *a*)-*d*) towards the end of the simulation, due to increased GWP over time for centralized generation. Increased GWP over time for centralized generation was also verified in (Barros et al., 2018), corroborating the results of our study.

Table 4 describes the OL long-term effects on GWP in greater detail. The GWP impacts are also significant.

3.2. Case study - general results

Our proposed methodology was applied to 35 Brazilian concession areas (concession areas with available data), as described in Fig. 9 and Table 5. Although Brazil currently has 105 concession areas (ANEEL, 2021c), most DG integration and electricity consumption was concentrated among 35 areas (ANEEL, 2021a). Thus, the results offer a proper overview of OL impacts. Nevertheless, small-scale concession areas were also included among the 35, ensuring a more thorough assessment (small-scale concession areas are particularly important when analyzing OL impacts on regulated tariffs, or relative OL impacts). Electricity consumption, DG generation, regulated tariffs, and average income for each concession area are described in Table 5.

Appendix A offers additional information on how the parameters were adapted/estimated for each of the 35 analyzed concession areas. Given the distinct parameters, the BDM, TAROT, and LCA were conducted/applied separately for each of the 35 concession areas.

The results are presented independently for each concession area, followed by OL impacts per state. Finally, the overall OL impacts for the equivalent concession area are listed. Only long-term results (2030) are shown for simplicity's sake.

3.2.1. Results for each concession area

The concession areas were ranked based on OL impacts. Only the most affected concession areas were listed in the graphs for simplicity's sake. The results for all concession areas are given in the supplementary material (Costa, 2022).

Fig. 10 shows the ranking for the most affected (by the OL) concession areas in terms of generated DG electricity (TWh/year). Contrary to common belief, the results show that *CEMIG-D*, which currently has the highest installed DG capacity, will not be the most affected area in terms of generated electricity. Rather, *AES Eletropaulo* is more affected for four main reasons:

(i) *AES Eletropaulo* is larger in terms of electricity consumption, i.e., it has higher market potential for DG integration (m_p) (ANEEL, 2021b);
(ii) *AES Eletropaulo* is located in a wealthier concession area (IBGE, 2022), increasing its maximum market fraction (m_{mf});
(iii) *AES Eletropaulo* has a higher share of residential DG (58%) (ANEEL, 2021a). Thus, its share of self-consumption (l) is lower (Alsol Energias, 2021), implying that prosumers are more reliant on electricity compensation from grid injections; and
(iv) Only prospective new prosumers are sensitive to OL with respect to purchasing decisions (DG systems), so substantial current installed DG capacity levels at *CEMIG-D* will be maintained, regardless of the regulatory changes.

It is important to assess the relative OL impacts (percentage terms) to consider the interests of small-scale concession areas. Fig. 11 offers a ranking similar to Fig. 10, in percentage terms (net metering is represented as 1 per unit). Small-scale concession areas will be significantly affected. It is important to mention that, although most small-scale

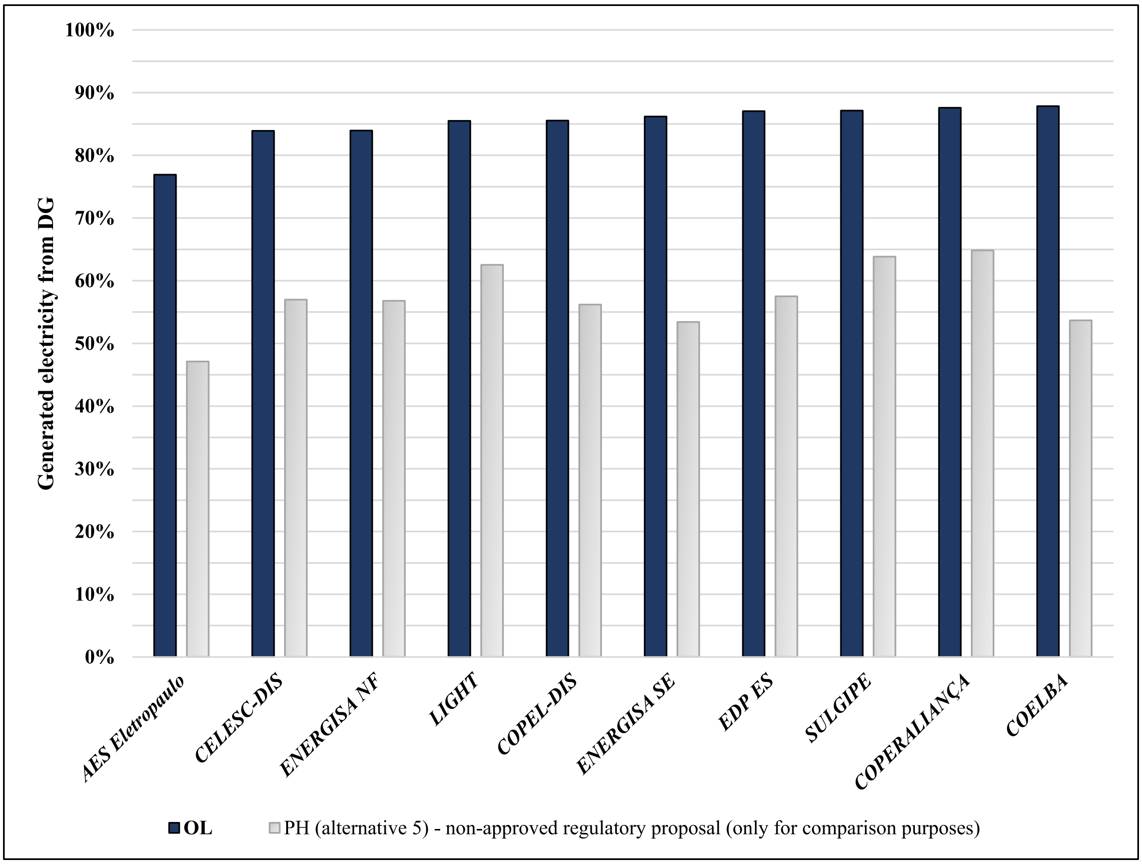

Fig. 11. Ranking the most affected concession areas in terms of the generated DG electricity in (%) for 2030.

concession areas currently have incipient installed DG capacities, they have future potential, which will be partially forfeited.

Fig. 12 shows the ranking of the most affected concession areas, in terms of PEI. *CPFL Paulista* is most affected, followed by *CEMIG-D*, since the OL states that only DG systems deployed after Jan/2023 will be subject to regulatory changes. Thus, substantial current installed DG capacity in *CEMIG-D* will not be subjected to regulatory changes. Nevertheless, impacts on *CEMIG-D*'s concession area are relatively high (second) given extensive DG potential (high tariffs and PSH), which is partially forfeited after the OL.

Fig. 13 shows a ranking of the most affected concession areas in terms of regulated tariffs. Different from the other rankings, Fig. 13 shows OL benefits in the form of reduced tariffs. *ENEL RJ* will be benefited the most since its tariff decreased the most. Interpreting these results is not so simple since tariffs are calculated numerically. However, the following factors may contribute to the extensive decrease in *ENEL RJ*'s tariff:

(i) *ENEL RJ* has high tariffs (4th highest (ANEEL, 2021b)), needed to cover its high costs; and
(ii) *ENEL RJ* will have a high E_G/E ratio in 2030 (the highest according to the BDM estimations), indicating notable penetration levels relative to market size. Item (*ii*) is mainly why small-scale concession areas also benefit significantly from tariff decreases in function of the OL, as shown in Fig. 13.

Before presenting the ranking of the most affected concession areas in terms of GWP, we need to assess the LCA results in (g CO_2 eq/kWh) (Fig. 14). Performing LCA for each concession area is important since emissions per (kWh) may vary significantly. A thorough literature review of LCA for PV systems (Antonanzas et al., 2019; Constantino et al., 2018; Akinyelea et al., 2017; Dones and Frischknecht, 1998; Eskew et al., 2018; Fu et al., 2015; Gazbour et al., 2018; Luo et al., 2018; Pacca et al., 2007; Peng et al., 2013; Perez and Fthenakis, 2011; Santoyo-Castelazo et al., 2021; Sherwani et al., 2010; Sumper et al., 2011; Zhai and Williams, 2010), as per Fig. 15, shows that our results agree with previous research on the topic. All results are presented in terms of average in Fig. 15, and results from the literature reviews are also considered. The Constantino et al. (2018), LCA study was most similar to this paper, according to Fig. 15, since it also studied Brazil and studied multi-crystalline silicon (multi-Si) modules. Finally, the ranking of the most affected concession areas, in terms of GWP, is given in Fig. 16. The results show that *AES Eletropaulo* was the most affected.

3.2.2. Results per state

Another important outcome is OL impact per state. The results do not represent the overall impacts in each state, since 35 out of 105 concession areas were analyzed. Nevertheless, this section provides meaningful conclusions on the OL.

Fig. 17 *a*) shows OL impact in terms of generated DG electricity, where *São Paulo* (the most affected state) is represented at 1 per unit. The most affected states are located in the southeast region (*São Paulo* and *Rio de Janeiro*), mainly given their high market potential for DG integration (m_p), and high levels of economic development (m_{mf}). Impacts on *Minas Gerais* state were not particularly high, mainly since there is only one large scale concessionaire in *Minas Gerais* compared to three consesisonairres in *São Paulo*, resulting in lower m_p for the former state.

Fig. 17 *b*) shows OL impacts per state in terms of PEI (*São Paulo* represented at 1 per unit). Similar to Fig. 17 *a*), the most affected states are located in the southeastern region. However, the difference between *São Paulo* and *Minas Gerais* is lower given the extensive DG potential in *Minas Gerais*.

Fig. 17 *c*) shows the OL effects per state in terms of regulated tariffs. The tariff for each state is calculated based on a weighted average (the

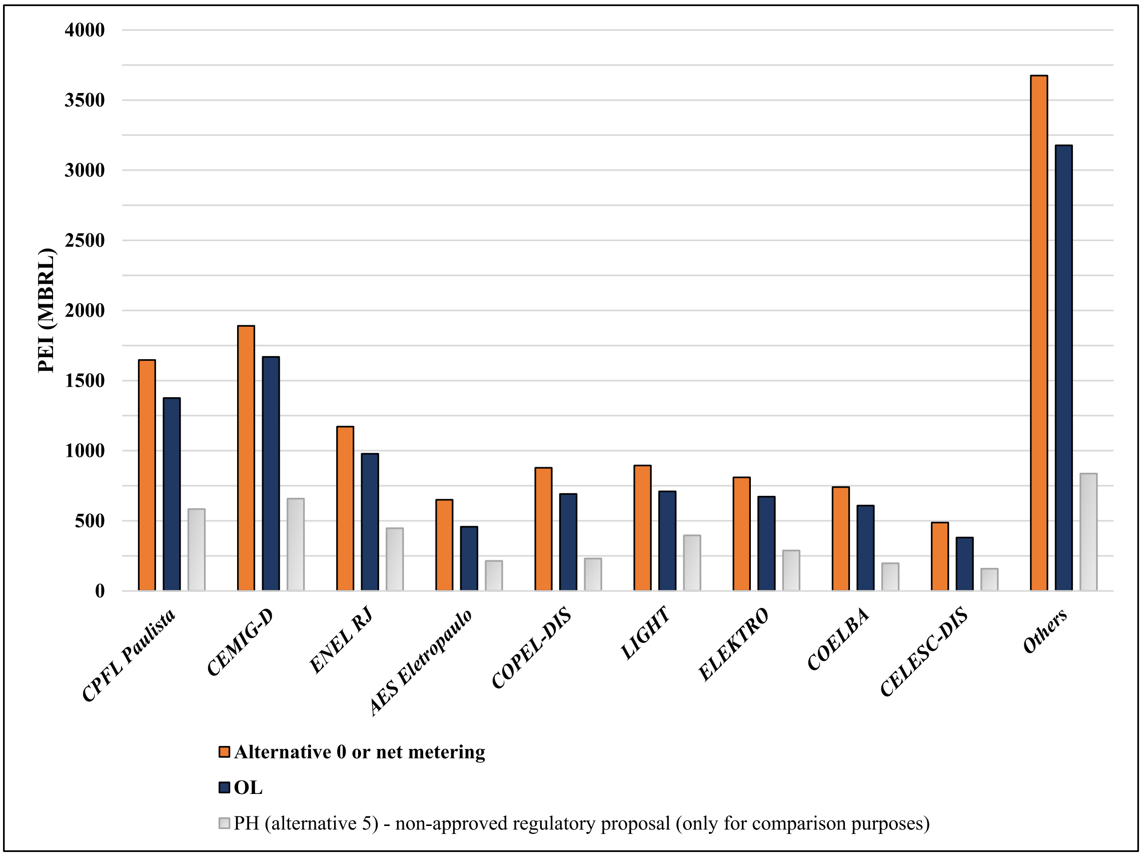

Fig. 12. Ranking the most affected concession areas in terms of PEI in (MBRL) for 2030.

weights are electricity consumption in the concession areas). Different from the other maps, Fig. 17 *c*) shows OL benefits, which are reduced tariffs. *Rio de Janeiro* is represented at 1 per unit, since it benefits the most (the greatest tariff reductions). *São Paulo* does not benefit substantially since electricity consumption there is massive. Therefore, the E_G/E ratio for *São Paulo* is relatively low (a justification for this was mentioned when evaluating *ENEL RJ*'s concession area).

Finally, OL impacts per state in terms of GWP are shown in Fig. 17 *d*) (*São Paulo* is represented at 1 per unit).

3.2.3. Results for the equivalent concession area

The equivalent concession area is defined as the sum of all 35 analyzed concession areas. Therefore, all results are summed except for regulated tariffs, which were weighted averages. The results are shown in Fig. 18 and Table 6. A negative sign implies that the OL decreases the quantity. On the other hand, a positive sign implies that the OL increases the quantity. The OL successfully mitigates tariff increases and reduces social inequality. However, there were negative consequences to the DG business, market welfare, and the environment. To put things into perspective, Brazil's electricity consumption corresponded to 474 (TWh) in 2020 (Engie, 2021). Therefore, the long-term OL impacts on GD-generated electricity is in the order of 1.4% of all of Brazil's electricity consumption (calculated based on 2020 demand). Regarding GWP, Brazil's electricity generation carbon footprint corresponded to 116 (Mt CO_{2eq}/year) in 2021 (Barros et al., 2018). Hence, the long-term OL impacts on GWP are in the order of 0.3% of the country's emissions from electricity generation (calculated based on the 2021 footprint). Brazil's electricity consumption and carbon footprint on electricity generation were 11.8% and 7.5% of the USA's ("EIA," 2021). Thus, OL impacts are in the order of 0.2% and 0.02% of the USA's electricity consumption and carbon footprint on electricity generation, respectively. Environmental impacts relative to the USA are not very significant given Brazil's high share of renewables.

4. Conclusions and policy implications

The societal effects of regulations can be massive, especially for regulations on distributed generation, since it has been increasingly deployed worldwide. Before regulatory changes are implemented, researchers must analyze/quantify their effects. This paper presented a methodology to holistically assess a new law for regulating distributed generation in Brazil. This methodology can also be applied to other countries/regions that will undergo regulatory changes to distributed generation (adaptations might be required depending on tariff regimes).

This paper demonstrated that Ordinary Law 14300 (OL) is worse than net metering from the prosumer and environmental points of view. However, it is significantly better than Public Hearing 25/2019, which was an older regulatory framework proposed by ANEEL that was not approved. Depending on the analyzed item, the Public Hearing's impact (alternative 5) could be more than four times higher. Therefore, it is fair to assume that prosumer interests were safeguarded comparing both regulatory frameworks. Naturally, Public Hearing 25/2019 resulted in lower tariffs over the long term, and was, therefore, superior from the conventional consumer's point of view.

Medium-term regulatory changes are needed if Brazil is to avoid tariff increases from continuous DG integration. However, Ordinary Law 14300 applications proved to be slightly premature for most concession areas for two main reasons:

(i) Distributed generation is still proportionally underdeveloped in Brazil (around 5% of the installed capacity); and
(ii) Most companies had positive surplus (91% of all companies in 2021). Thus, in most cases, current regulations could be kept (net metering) for a couple of years, since short-term tariff impacts

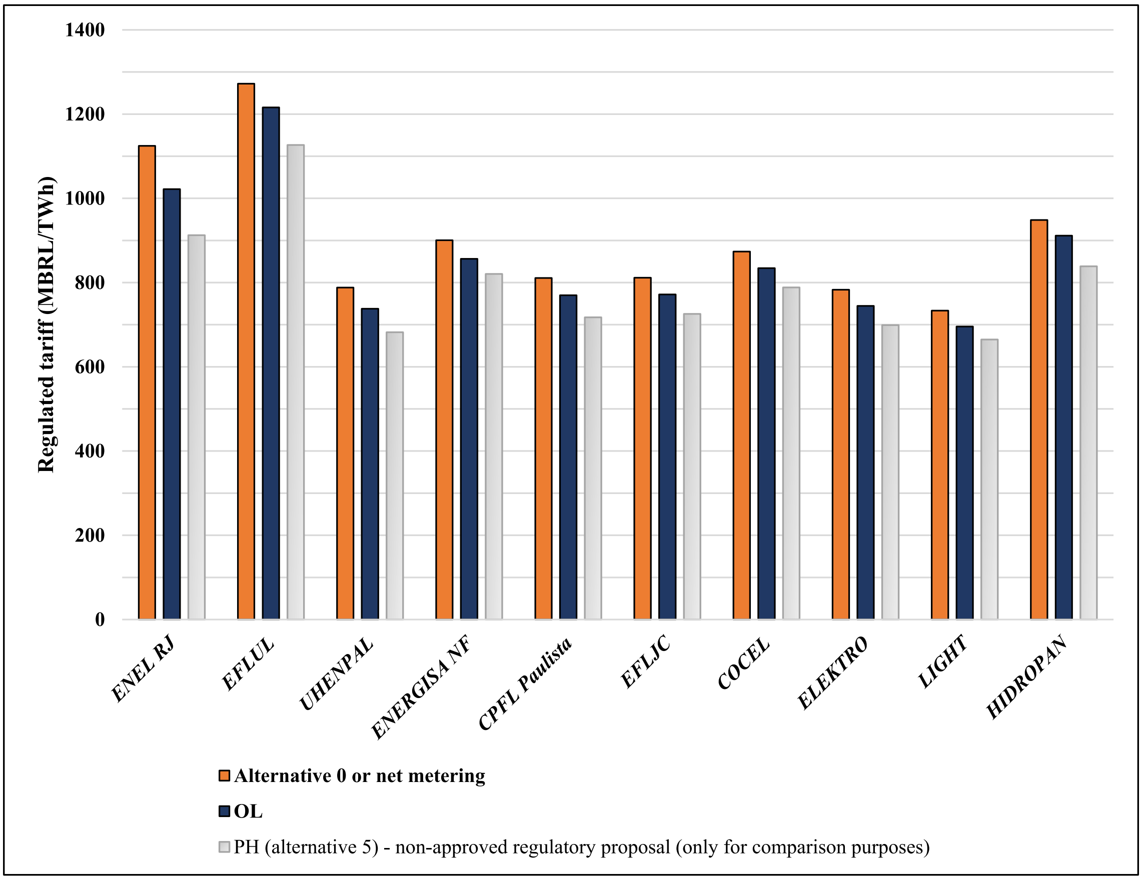

Fig. 13. Ranking the most affected concession areas in terms of regulated tariffs in (MBRL/TWh) for 2030.

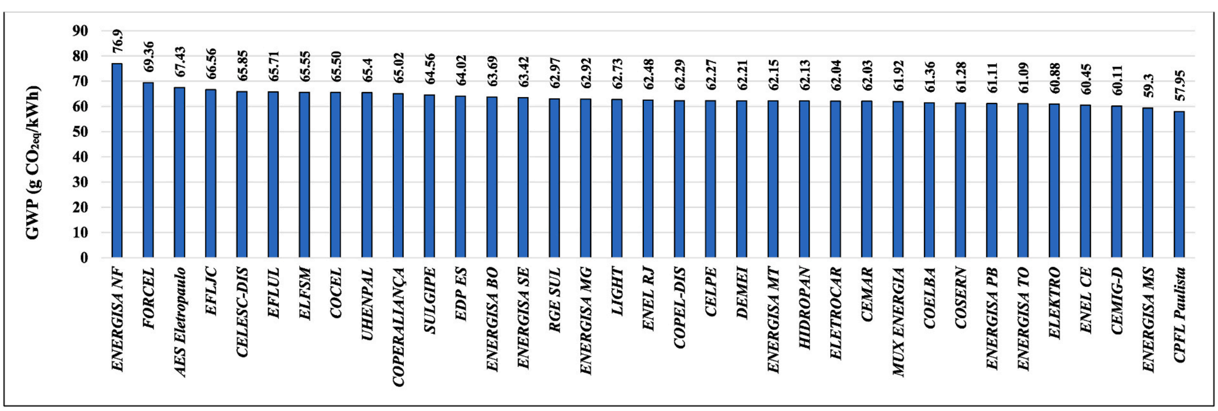

Fig. 14. LCA results in (g CO_2 eq/kWh).

would be limited. In the long term (2030), the proposed model estimates a negative surplus for 37% of all companies if net metering is maintained, reinforcing that regulatory changes are required before then.

This proposed methodology estimates that, over the long term, Ordinary Law 14300 will lead to 6.60 (TWh/year) losses, or 11.3% of DG-generated electricity, 2.12 billion (BRL/year), or 16.5% socioeconomic welfare, and emissions at 0.35 (Mt CO_{2eq}/year), or 9.5% of the 35 analyzed concession areas, compared to net metering. Impacts are in the order of 1.4% of Brazil's electricity consumption, and 0.3% of Brazil's carbon footprint from electricity generation relative to Brazil's current situation. Regarding the regulatory fairness, we verified significant improvements, since tariffs are expected to decrease by 27.11 million (BRL/TWh), or 3.6% on average. Therefore, Ordinary Law 14300 favors conventional consumers (consumers who do not own distributed generation systems), and reasonably decreases social inequality compared to net metering. Future studies should assess if the trade-offs reported here are appropriate, based on multi-objective optimization.

The results indicate that *AES Eletropaulo*, *LIGHT*, and *CPFL Paulista* will be most affected by Ordinary Law 14300 in terms of DG-generated electricity (1.22 (TWh/year), 0.84 (TWh/year), and 0.64 (TWh/year), respectively. *CPFL Paulista*, *CEMIG-D*, and *ENEL RJ* will be most affected in terms of socioeconomic welfare (270.8 (MBRL/year), 221.5 (MBRL/year), and 193.2 (MBRL/year), respectively. *ENEL RJ*, *EFLUL*, and *UHENPAL* will be most affected (favored) in terms of electricity tariffs

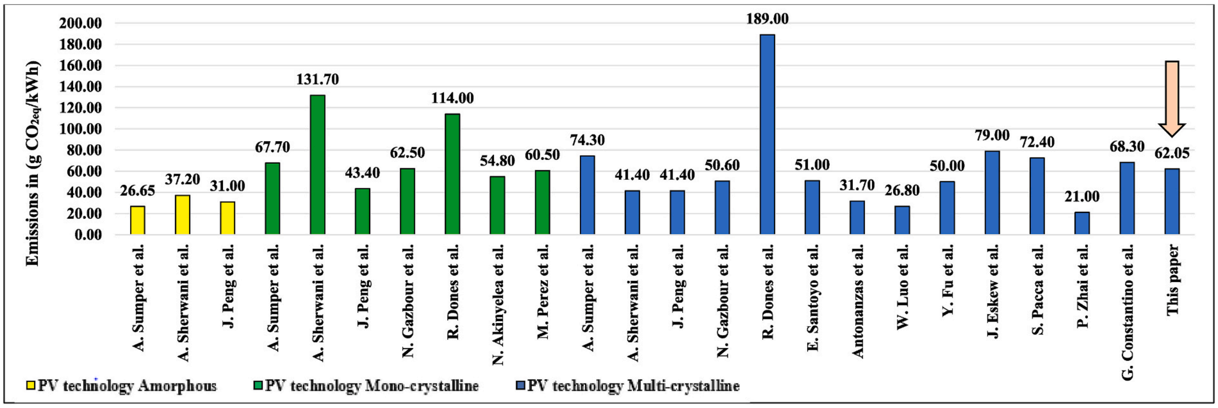

Fig. 15. Comparison between this paper's LCA results and previous research on the topic.

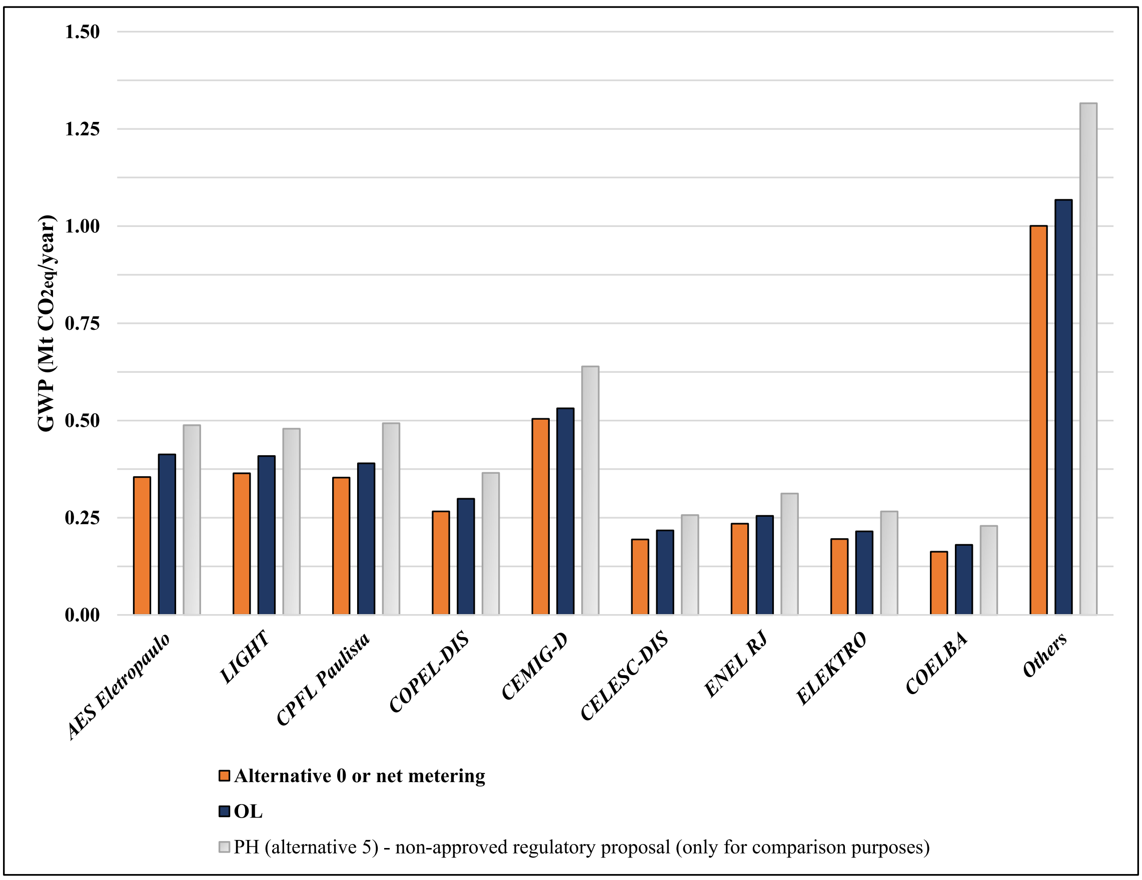

Fig. 16. Ranking of the most affected concession areas in terms of the GWP in (Mt CO_{2eq}/year) for the year 2030.

(102.8 (MBRL/TWh), 56.5 (MBRL/TWh), and 50.4 (MBRL/TWh), respectively. *AES Eletropaulo*, *LIGHT*, and *CPFL Paulista* will be most affected in terms of global warming potential (0.058 (Mt CO_{2eq}/year), 0.044 (Mt CO_{2eq}/year), and 0.037 (Mt CO_{2eq}/year), respectively. *São Paulo* and *Rio de Janeiro* are expected to be the most affected states, given their high market potential (electricity consumption), high economic development (per capita income), and future distributed generation integration relative to *Minas Gerais* state. The early stage substantial deployment of distributed generation in *Minas Gerais* contributed to mitigating Ordinary Law 14300 impacts, since only systems implemented after Jan/2023 will be subject to regulatory changes. We should emphasize, however, that the estimations of the proposed model depend on several factors distinct to each concession area (e.g., initial tariff, amount of peak sun hours, share of self-consumption, life cycle assessment results, the influence of distributed generation on the operational costs and energy loss costs, etc.), so the results are a combination of all these factors.

This paper showed that the new law's impacts considerably differ depending on the concession area. Therefore, implementing a unified regulation for all of Brazil proved to be detrimental. While this is true, proposing a regulatory framework that simultaneously considers distributed generation business, market welfare, regulated tariffs, and environmental concerns, while seeking to optimize these aspects in each region, is a daunting challenge. Therefore, more studies are needed on the topic to guide holistic/optimal regulation on distributed generation. Furthermore, other aspects related to Ordinary Law 14300 should be

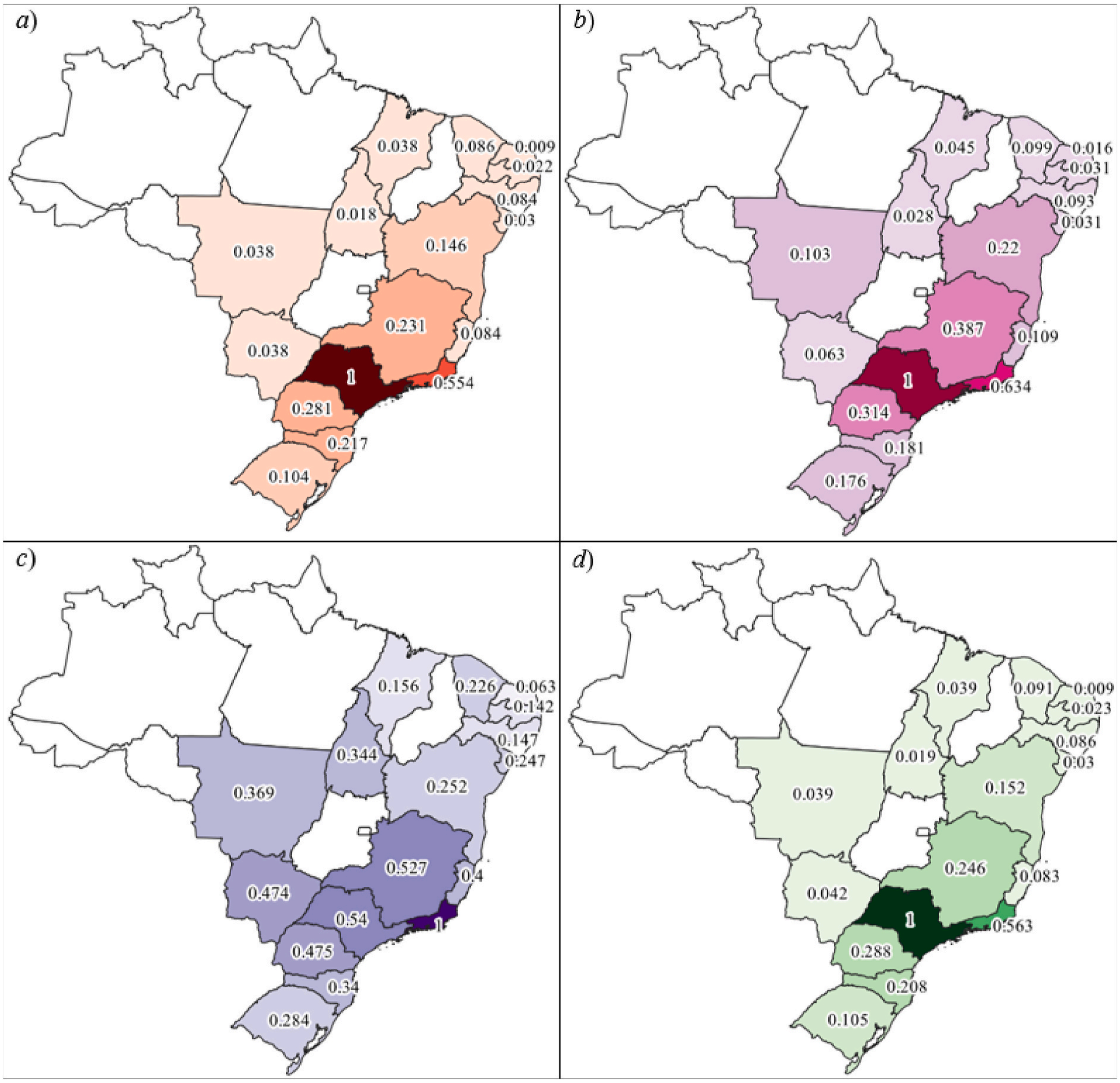

Fig. 17. OL impacts per state in terms of *a*) DG-generated electricity, *b*) PEI, *c*) regulated tariffs, and *d*) GWP.

assessed directly in future studies (e.g., legal aspects), since we focused on prosumer compensation, like focusing on questions like how specific compensation will be accounted for after 2030. OL offers fair/proper rules based on the costs and benefits of distributed generation, yet the calculation methodology is not yet clear, so more studies on the theme would be warranted after the calculation methodology is published. Moreover, we emphasize that, although our proposed model allows the regulation impacts over the long term to be assessed, the model must be applied annually with updated input data to further enhance accuracy over time. Lastly, shock impacts were not considered in the model since implementing regulatory changes has been discussed since 2019, and OL ensures that those who install distributed generation systems within one year after the law's implementation will not be subject to regulatory changes. So, there is/has been a reasonable transition period. That being said, it would be beneficial to integrate this feature into the model in future studies, especially for more sudden regulatory changes.

CRediT authorship contribution statement

Vinicius B.F. Costa: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Rafael S. Capaz:** Conceptualization, Software, Investigation, Writing – original draft, Writing – review & editing. **Patrícia F. Silva:** Conceptualization, Writing – review & editing. **Gabriel Doyle:** Conceptualization, Writing – review & editing. **Giancarlo Aquila:** Conceptualization, Writing – review & editing. **Éden O. Coelho:** Conceptualization, Writing – review & editing. **Eliane de Lorenci:** Conceptualization, Writing – review & editing. **Lígia C. Pereira:** Conceptualization, Writing – review & editing. **Letícia B. Maciel:** Conceptualization, Writing – review & editing. **Pedro P. Balestrassi:** Conceptualization, Writing – review & editing. **Benedito D. Bonatto:** Conceptualization, Writing – review & editing. **Luiz C. da Silva:** Conceptualization, Writing – review & editing.

Declaration of competing interest

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

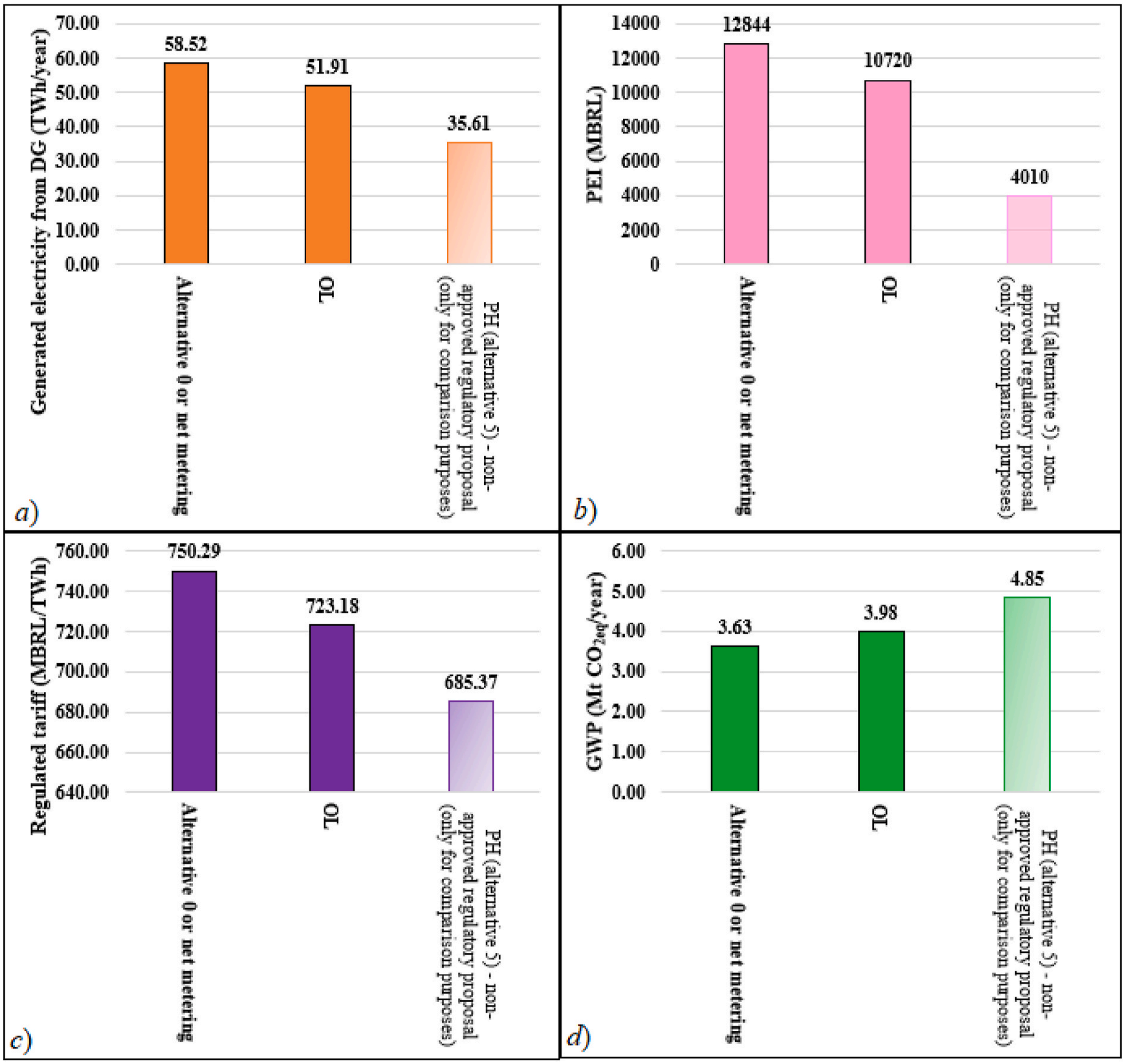

Fig. 18. OL impacts on the equivalent concession area in terms of *a)* DG-generated electricity DG, *b)* PEI, *c)* regulated tariffs, and *d)* GWP.

Table 6
OL impacts on the equivalent concession area (year 2030).

	Generated electricity from DG	PEI	Regulated tariff	GWP
Absolut impact of OL	**−6.60 (TWh/year)**	**−2123 (MBRL)**	**−27.11 (MBRL/TWh)**	**0.346 (Mt CO_{2eq}/ year)**
Relative impact of OL in (%)	**−11.3**	**−16.5**	**−3.6**	**9.5**
Absolut impact of PH (alternative 5) – non-approved regulatory proposal (only for comparison purposes)	−22.91 (TWh/year)	−8834 (MBRL)	−64.92 (MBRL/TWh)	1.214 (Mt CO_{2eq}/ year)
Relative impact of PH in (%) (alternative 5) – non-approved regulatory proposal (only for comparison purposes)	−39.2	−68.8	−8.7	33.4

Data availability

The data used are made available as supplementary material, as specified in the paper

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Appendix A. Parameters

General information on how to obtain the parameters values is provided in Table A1 (all parameters are defined in the list of parameters). Furthermore, it also shows the parameters values obtained for *CPFL Paulista*. The values were estimated based on PV DG systems since they represent more than 99% of connections in Brazil (ANEEL, 2021a). It is emphasized that further information regarding the obtention of the TAROT model's parameters (e.g., equations and mathematical proofs) can be found in (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).

Table A1
Parameters obtention

Parameter	Refs. of interest	Notes	Value for *CPFL Paulista*'s concession area
n	Description of the OL (House of Representatives, 2019).	Fig. 1 summarize the OL.	Depends on the year
P_{BT}	Description of the OL (House of Representatives, 2019). Previously published studies from the regulatory agency (ANEEL, 2017a); Historical series of DG integration (ANEEL, 2021a).	Fig. 1 summarize the OL; The payback time is assumed to be dependent on $\{l + (1 - l)n\}$, as described in Equation (5). For increased accuracy, a weighted average of the payback of commercial and residential DG systems is conducted (the weights are the installed capacities of DG of each class).	Depends on the year
p_B	Historical series of DG integration (ANEEL, 2021a).	Obtained by the minimum squares method (comparison between the BDM and the historical series). Fig. A1 demonstrates that such an approach is highly accurate.	8.96E−05 (years^{-1})
q_B	Historical series of DG integration (ANEEL, 2021a).	Obtained by the minimum squares method (comparison between the BDM and the historical series). Fig. A1 demonstrates that such an approach is highly accurate.	8.54E−01 (years^{-1})
P_{BS}	Previously published studies from the regulatory agency (ANEEL, 2017a); Income studies (IBGE, 2022).	ANEEL estimates P_{BS} as 0.4 in the context of the whole country (ANEEL, 2017a). To adapt it to a specific region, Equation (4) is used.	0.34
s_1	Previously published studies from the regulatory agency (ANEEL, 2017a); Specific market research studies of PV DG systems (Greener, 2021).	–	163.07 (MR$/TWh)
m_p	Reports of tariff review processes (ANEEL, 2021b).	Currently, all captive consumers are allowed to integrate a DG system into the grid; however, it is emphasized that this does not mean that all consumers will do so due to the m_{mf}, i.e., due to economic limitations. Due to unrestricted authorization, m_p is assumed to be equal to the consumed electricity (ANEEL assumes a similar approach in (ANEEL, 2017a)).	23.59 (TWh)
e'	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (V. Costa et al., 2021a).	Equation (9).	262.4 (MR$/TWh)
f	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (V. Costa et al., 2021a).	Power flow simulations are required. However, Brazilian distribution companies do not publicly disclose their grid topologies yet. Therefore, simulations were carried out in the OpenDSS® software for a test grid with characteristics of real distribution systems (Radatz, 2015).	2.49E+07 (MR$^{2})
g	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (V. Costa et al., 2021a).	Power flow simulations are required. However, Brazilian distribution companies do not publicly disclose their grid topologies yet. Therefore, simulations were carried out in the OpenDSS® software for a test grid with characteristics of real distribution systems (Radatz, 2015).	−1.44E+07 (MR$^{2})
T	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	793.37 (MR$/TWh)
E	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	23.59 (TWh)
t	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	34.0%
e	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	Equation (8).	454.5 (MR$/TWh)
p	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	12404.3 (MR$^{2}/TWh^2)
μ	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	23.3%
k	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018;	–	16.0%

(*continued on next page*)

Table A1 (*continued*)

Parameter	Refs. of interest	Notes	Value for *CPFL Paulista*'s concession area
	Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).		
a	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	5760.7 (MR$/TWh)
b	Reports of tariff review processes (ANEEL, 2021b); TAROT model studies (Arango et al., 2018, 2017; Cortez, 2018; Cortez et al., 2018; Costa et al., 2019; V. Costa et al., 2021a; V. B. F. Costa et al., 2021b).	–	210.5 (MR$/TWh^2)
ε	Specialized studies (Modiano, n.d.).	For increased accuracy, a weighted average of the demand elasticities of the commercial, industrial, and residential consumption classes is conducted (the weights are the electricity consumptions of each class). The elasticities of the commercial, industrial, and residential classes are estimated as 0.062, 0.451, and 0.118, respectively (Modiano, n.d.).	15.97%
l	Specialized studies (Alsol Energias, 2021).	For increased accuracy, a weighted average of the self-consumptions of the commercial, industrial, and residential consumption classes is conducted (the weights are the installed capacities of DG of each class). The self-consumptions of the commercial, industrial, and residential classes are estimated as 70%, 50%, and 30% (Alsol Energias, 2021).	45.32%

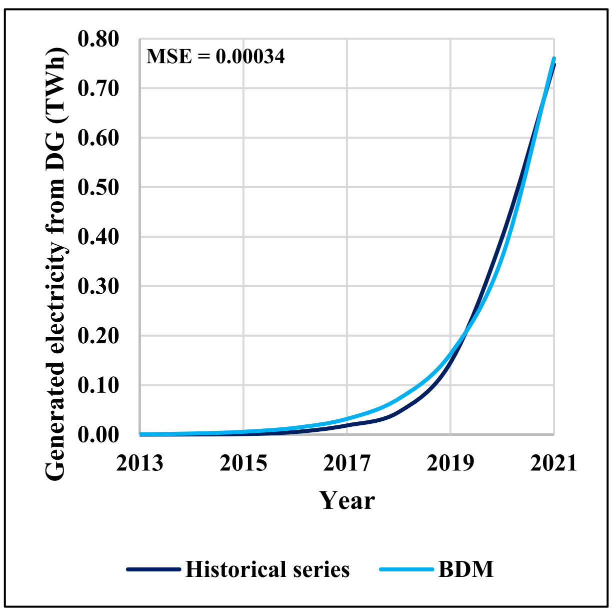

Fig. A.1. Historical series and BDM (*CPFL Paulista*).

The mathematical proof of the calculation of the P_{BS} parameter is conducted in Equation (A.1):

$$m_{mf} = A_I m_{mf(M)} \Rightarrow e^{-P_{BS}P_{BT}} = A_I e^{-P_{BS(M)}P_{BT}} \Rightarrow -P_{BS}P_{BT} = \ln A_I - P_{BS(M)}P_{BT} \Rightarrow P_{BS} = P_{BS(M)} - \frac{\ln A_I}{P_{BT}} \tag{A.1}$$

where:

The subscript (M) regards the mean parameters estimated in the context of the whole country;

The maximum market fraction of a specific region is assumed to be proportional to its average income, justifying the relation $m_{mf} = A_I m_{mf(M)}$.

Regarding the parameters' adaptation/estimation for each of the 35 analyzed concession areas, the majority of them were sorted by concession area (20 parameters or 90.9%). Due to lack of data, two parameters were sorted by state, i.e., distances and P_{BS}. The same references indicated in Tables A1 and Tables B1-B.2 were used to obtain the parameters.

Regarding the distances used in the LCA, seven of the busiest Brazilian ports were considered for technology importation (the closest port to each state was assumed). The remainder of the calculation of the distances was conducted analogously to Table B1 (estimations vary by state).

Appendix B. LCA Considerations and LCI

The following assumptions were considered to conduct the LCA:

- The system's purpose is to supply electricity. Therefore, it is assumed that the electricity forfeited due to the decreased demand for DG systems must be supplied by the conventional Brazilian grid (centralized generation). Consequently, the OL indirectly increase the usage of the conventional grid;
- The LCIA method is applied annually based on the forecasted generated electricity from DG obtained by the BDM, i.e., based on the variable E_G previously defined in (2);
- PV DG systems represent more than 99% of connections in Brazil (ANEEL, 2021a). Among PV technologies, multi-crystalline silicon (multi-Si) modules are among the most deployed (Rakesh Tej Kumar et al., 2018). Therefore, the LCA is carried out based on multi-Si modules;
- Modules and inverters are the two main components of the PV system concerning environmental impact since their manufacturing is resource-intensive (Abdoli et al., 2020). Therefore, DC cables and installation material are addressed as cut-off criteria;
- Manufacturing in China and Europe (Germany) is assumed for the PV modules and inverters, respectively, since these regions present significant manufacturing of such technologies (Mundo-Hernández et al., 2014; Shubbak, 2019) and reliable LCI data. It is emphasized that Brazil is still incipient in that regard; hence, assuming importation of technologies is a more valid approach;
- Disposal/recycling is not considered since the system's lifetime is much longer than the forecast horizon;
- The software OpenLCA is used due to its simplicity and notoriety;

Tables B1-B.2 describe the transport and usage phases of the LCI for *CPFL Paulista*.

Table B.1
Transport phase

Technology specification	Type of transport	Weight (kg) [a]	Distance (km) [b]	Distance multiplied by weight (t·km)	Notes
PV modules totaling 10 (kWp)	Ship (importation)	833	20,476	17,056	Nautical distance from Shanghai port to Santos port. [c]
	Lorry (internal distribution)	833	2017	1680	Estimated lorry distance in China plus Brazil.
Inverter of 10 (kW)	Ship (importation)	45	10,525	474	Nautical distance from Hamburg port to Santos port. [d]
	Lorry (internal distribution)	45	458	21	Estimated lorry distance in Germany plus Brazil.

[a] Typical weight.
[b] Satellite distance.
[c] Shanghai port is among the busiest ones in China (Shan et al., 2014).
[d] Hamburg port is among the busiest ones in Germany (Slack, 1999).

Table B.2
Usage phase

Technology specification	Amount of PSH (hours/year)	PV system efficiency	Generated electricity (kWh/year)	Notes
PV system of 10 (kWp)	2001 (ANEEL, 2017)	0.8 (Al Riza and Gilani, 2014)	16,008	Applied equation (Al Riza and Gilani, 2014): [a] $E_G^{'} = PP_{SH}\eta$ (B.1)

[a] Parameters defined in the list of parameters.

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Glossary

100a: horizon of 100 years
ANEEL: Brazilian Electricity Regulatory Agency
BAU: business as usual
BDM: Bass diffusion model
CAPEX: capital expenditure
CNPE: National Council for Energy Policies
DG: distributed generation
DR: demand response
ECA: economic consumer added
ESS: energy storage systems
EVA: economic value added
EWA: economic wealth added
FEE: financial economical equilibrium
FIT: feed-in-tariff
GDP: gross domestic product
GHG: greenhouse gases
GWP: global warming potential
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organisation for Standardisation
LCA: life cycle assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
MSE: mean squared error
multi-Si: multi-crystalline silicon
NREL: National Renewable Energy Laboratory
O&M: operational and maintenance
OL: Ordinary Law 14300
OPEX: operational expenditure
PEI: performance index
PH: Public Hearing 25/2019 (the ANEEL's proposal)
PSH: peak sun hours
PV: photovoltaic
RPF: reverse power flow
TAROT: optimized tariff
TOU: time-of-use