FEDERAL UNIVERSITY OF ITAJUBÁ

ELECTRICAL ENGINEERING GRADUATE PROGRAM

HOLISTIC DEVELOPMENT OF INTELLIGENT ELECTRICITY MARKETS USING THE TAROT – OPTIMIZED TARIFF – WITH TECHNICAL, ECONOMIC, REGULATORY, AND ENVIRONMENTAL MODELS

Vinicius Braga Ferreira da Costa

February 21st, 2024

Itajubá-MG

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Final thesis submitted to the Electrical Engineering Graduate Program as one of the requirements to obtain the Ph.D. title in Electrical Engineering.

Concentration area: Electrical Power Systems

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Abstract

The deployment of renewable distributed generation (DG) and energy storage systems (ESSs) has been continuously increasing in several countries due to ongoing technical and economic breakthroughs and the implementation of incentive policies. In Brazil, the deployment of on-grid DG under a compensation scheme began in 2012, when the first specific regulation was published (Normative Resolution - REN 482). REN 482 implemented the net metering policy to boost DG installed capacity, as such a policy is highly beneficial for prosumers. However, DG installed capacity has increased substantially, causing decision-makers to rethink the regulatory framework and seek a more balanced solution through Ordinary Law 14300/2022 (OL). In this context, it is clear that regulatory aspects are in the spotlight in Brazil, given their importance to society and the need for changes. However, there is a lack of robust and holistic regulatory models that can be used to implement efficient regulatory frameworks. Thus, analyses are typically empirical. In this context, this thesis fills an essential research gap by developing cutting-edge regulatory models. First, it adapts the optimized tariff model - TAROT (socioeconomic regulated electricity market model) and the Bass Diffusion Model - BDM (forecasting model of technology integration) to the context of DG and ESSs to evaluate the consequences of increasing penetration levels in the market. Second, it uses the TAROT, BDM, and Life Cycle Assessment - LCA (environmental impact analysis technique) to holistically analyze the impacts of the OL, taking into account socioeconomic and environmental indicators. Third, it combines the TAROT, BDM, and LCA into a multi-objective optimization (MOO) approach to obtain holistic and optimal regulatory frameworks for DG. The optimal solutions are compared to the OL to evaluate whether the law achieved a satisfactory trade-off. Fourth, it extends the proposed model by assuming the co-existence between conventional markets and Community-Based Markets (CBMs), defined as groups of members that share common interests, such as trading electricity from DG. Lastly, it introduces a scenario-based bi-level optimization problem to account for the random locational aspect of DG systems. Results demonstrate that the OL is successful in mitigating tariff raises and reducing social inequality. By contrast, there are negative implications to the DG business, market welfare, and the environment, as socioeconomic welfare losses at 2.12 billion R$/year or 0.42 billion US$/year, and emissions at 0.35 Mt CO_2-eq/year are estimated in total for the 35 analyzed concession areas. The MOO approach indicates that the OL is a dominated or non-optimal solution since it is not located on the Pareto frontiers. Thus, while reductions in the compensation for the electricity injected into the grid are necessary in Brazil, the OL defined the compensation empirically, without the application of well-defined methods, implying a sub-optimal solution. Assuming the Euclidian knee points, the optimal solutions implied benefits of around 24% in terms of electricity tariff affordability, with small losses of roughly 6% in terms of socioeconomic welfare and global warming potential. Additionally, one can conclude that CBMs can be significantly beneficial in mitigating energy poverty in Brazil, as benefits of around 1.4% were estimated assuming the whole regulated market, or 16.5% assuming only the CBMs participants. However, such benefits would only take place if low-income consumers could participate in the CBMs. Lastly, the bi-level problem demonstrates the importance of assuming the uncertainties associated with DG integration.

Keywords: intelligent electricity markets, bi-level optimization, community-based markets, distributed energy resources, energy poverty, environmental aspects, multi-objective optimization, regulatory framework, socioeconomic welfare.

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CONTENTS

List of figures

LIST OF TABLES

LIST OF ACRONYMS

ANEEL	Brazilian Electricity Regulatory Agency
BDM	Bass diffusion model
BPF	Branch power flow
CAG	COVID-account group
CAPEX	Capital expenditures
CBM	Community-based market
CDF	Cumulative distribution function
CNPE	National Council for Energy Policies
DER	Distributed energy resource
DG	Distributed generation
DICOPT	Discrete and Continuous Optimizer
DISCO	Distribution company
DR	Demand response
ECA	Economic consumer added
ESS	Energy storage system
EV	Electric vehicle
EVA	Economic value added
EWA	Economic wealth added
FCEV	Fuel cell electric vehicle
FEE	Financial economic equilibrium
FIT	Feed-in-tariff
GAMS	General Algebraic Modeling System
GWP	Global warming potential
IBGE	Brazilian Institute of Geography and Statistics
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCOE	Levelized cost of electricity
LP	Linear programming
MINLP	Mixed integer non-linear programming
MOO	Multi-objective optimization
Multi-Si	Multi-crystalline silicon
NCAG	Non-covid-account group
NLP	Non-linear programming
NR	Normative resolution

NREL	National Renewable Energy Laboratory
O&M	Operation & maintenance
OL	Ordinary Law 14300/2022
OPEX	Operational expenditures
PDF	Probability density function
PEI	Performance index
PH	Public Hearing 25/2019
PRORET	Tariff review procedures
PSH	Peak sun hours
PV	Photovoltaic
RNG	Random number generation
ROI	Return on investment
RQ	Research question
SCIP	Solving Constraint Integer Programs
TAROT	Optimized tariff regulated electricity market model
TOU	Time-of-use tariff
TSEE	Electrical energy social tariff
UN	United Nations
V2G	Vehicle-to-grid
WACC	Weighted average cost of capital

NOMENCLATURE

Given that the model presented in Chapter 6 is very different from the other chapters, it was necessary to use distinct nomenclatures. Thus, the nomenclature is separated into two tables (Chapters 3 to 5 and Chapter 6)

CHAPTERS 3 TO 5.

Sets	Description	Unit
O, I, and P	Off-peak, intermediate, and peak periods, respectively	
$r \in \{0, \ldots, r_1\}$	Percentiles of consumers in critical energy poverty conditions	%
p and c	Prosumers and consumers, respectively	
$t \in \{t_0, \ldots, t_1\}$	Time	Year
Scalars	**Description**	**Unit**
M	Big M (sufficiently big number)	%
p	Conventional energy loss costs scalar	$MR\$^2/TWh^2$
b	Degree of satisfaction with the consumed electricity	$MR\$/TWh^2$
C_I	DISCO's costs related to mobile and real estate infrastructures	MR$
C_C	DISCO's energy purchase costs	MR$
C_A	DISCO's O&M costs	MR$
O_R	DISCO's revenues from secondary activities	MR$
E_S	DISCO's sector charges	MR$
C_T	DISCO's transmission costs	MR$
t_1	Final year of analysis	Year
d	Grid depreciation scalar	%
k	Hurdle rate for aggregation of value to the DISCO	%
q_B	Imitation scalar	$Year^{-1}$
t_0	Initial year of analysis	Year
p_B	Innovation scalar	$Year^{-1}$
A_G	LCA results for DG	Mt CO_2-eq/TWh
s	LCOE	MR$/TWh
χ_{Tl}	Lower boundary of the annual tariff variation	%
χ_{nl} or $\chi_{n_r l}$	Lower boundary of the annual variation concerning the compensation for the electricity injected into the grid	%
$\chi_{n_l l}$	Lower boundary of the annual variation concerning the compensation for the electricity commercialized locally	%
$K_{n_l l}$	Lower boundary of the compensation for the electricity commercialized locally in the CBM	%
K_{nl} or $K_{n_r l}$	Lower boundary of the compensation for the electricity injected into the grid	%
K_{Tl}	Lower boundary of the regulated electricity tariff	MR$/TWh
m_p	Market potential for deploying DG systems	TWh
z_{N1}	Nadir point of function 1	MR$
z_{N2}	Nadir point of function 2	[a]
e	Operational costs scalar	MR$/TWh
P_{BS}	Payback sensitivity	$Year^{-1}$
g	Proportional energy loss cost scalar	$MR\$^2$
f	Quadratic energy loss cost scalar	$MR\$^2$
λ	Ratio of generated electricity from DG used in each period	%

μ	Sales taxes scalar	%
e'	Scalar of the influence of DG on operational costs	MR$/TWh
l	Self-consumption ratio	%
t_t	Tax fee scalar	%
δ	Time frame in which changes in the design variables influence investments in DG	Year
χ_{Tu}	Upper boundary of the annual tariff variation	%
χ_{nu} or $\chi_{n_r u}$	Upper boundary of the annual variation concerning the compensation for the electricity injected into the grid	%
$\chi_{n_l u}$	Upper boundary of the annual variation concerning the compensation for the electricity commercialized locally	%
$K_{n_l u}$	Upper boundary of the compensation for the electricity commercialized locally in the CBM	%
K_{nu} or $K_{n_r u}$	Upper boundary of the compensation for the electricity injected into the grid	%
K_{Tu}	Upper boundary of the regulated electricity tariff	MR$/TWh
z_{U1}	Utopia point of function 1	MR$
z_{U2}	Utopia point of function 2	[a]
α	Weight assigned to function 1 in the MOO problem	%
r_W	Weighted average cost of capital	%
a	Willingness to consume electricity	MR$/TWh
Parameters	**Description**	**Unit**
$E_{GB}(t)$	Benchmark generated electricity from DG	TWh
$F(t)$	CDF	%
$EF(r)$	Electricity consumption (energy poverty context)	TWh
$A_C(t)$	LCA results for centralized generation	Mt CO_2-eq/TWh
$f(t)$	PDF	%
$W(r)$	Wages	MR$
Binary variables	**Description**	**Unit**
$x(t)$	Injection of electricity into the grid	%
$y(t)$	Local commercialization in the CBM	%
Continuous variables	**Description**	**Unit**
$Y(t)$	Capital yield	MR$
$n_l(t)$	Compensation for the electricity commercialized locally in the CBM	%
$n(t)$ or $n_r(t)$	Compensation for the electricity injected into the grid	%
$E_r(t)$	Consumers' electricity consumption from the grid	TWh
$C_D(t)$	DG systems' CAPEX and OPEX	MR$
$EVA(t)$	DISCO surplus	MR$
$ECA(t)$	Economic consumer added	MR$
$P(t)$	Electricity consumption ratio	%
$[PEI[EEP(t)]]_{with\ y(t)=0}$	Electricity expenses assuming the absence of CBMs	%
$[PEI[EEP(t)]]_{with\ binary\ y(t)}$	Electricity expenses assuming the presence of CBMs	%
$EEP(t)$	Electricity expenses in percentage terms	%
$U(t)$	Energy economic utility	MR$
$H(t)$	Energy loss cost	MR$
$E_G(t)$	Generated electricity from DG	TWh
$GWP(t)$	Global warming potential	Mt CO_2-eq
$B(t)$	Grid investment	MR$
$m_{mf}(t)$	Maximum market fraction	%
$Q(t)$	Operational costs	MR$
$B^*(t)$	Optimal grid investment	MR$

$C(t)$	Overall DISCO's costs	MR$
$E(t)$	Overall electricity consumption	TWh
$P_{BT}(t)$	Payback time	Year
$PEI[EEP(t)]$	PEI associated with energy poverty issues	%
$PEI[EWA(t), CGWP(t)]$	PEI associated with socioeconomic welfare and cost of global warming	MR$
$PEI[T(t)]$	PEI associated with the regulated electricity tariff	MR$/TWh
PEI	Performance index	MR$
$E_{pr}(t)$	Prosumers' electricity consumption from the grid	TWh
$C_1(t)$	Regulated DISCO's costs related to operational expenses, energy loss, and grid depreciation	MR$
$T(t)$	Regulated electricity tariff	MR$/TWh
$R(t)$	Revenue or electricity bill paid to the DISCO	MR$
$EWA(t)$	Socioeconomic welfare	MR$
$TRIB_P(t)$	Tributes over profits	MR$
$TRIB_S(t)$	Tributes over sales	MR$
$\Delta PEI[EEP(t)]$	Variation in electricity expenses	%

[a] In Section 5.3, the unit is MR$/TWh, whereas in Section 5.4, the unit is % since different functions are considered in the MOO problem ($PEI[T(t)]$ and $PEI[EEP(t)]$, respectively).

CHAPTER 6.

Sets	Description	Unit
i	Bus	p.u.
j	Bus	p.u.
k	Bus	p.u.
y	Long-term periods	Years
t	Short-term periods	Hours
Scalars	**Description**	**Unit**
S_{base}	Base apparent power	kVA
PBT_{base}	Base or original payback time	Years
T_{base}	Base or original regulated electricity tariff	MR$/TWh
ϑ	Conversion factor	kWh/TWh
p'	Cost of energy losses	MR$/TWh
$s_{decrease}$	Decreases in CAPEX and OPEX over time	p.u.
$PBT_{decrease}$	Decreases in the payback over time due to falling technology costs	p.u.
y_1	Final year of analysis	Year
δ	Fixed connection costs	p.u.
d	grid depreciation	p.u.
q_B	Imitation scalar	Years^{-1}
y_0	Initial year of analysis	Year
p_B	Innovation scalar	Years^{-1}
w	Iteration	p.u.
A_{dg}	Life cycle emissions of electricity from DG	Mt $CO_{2\text{-eq}}$/TWh
ϟ_{nl}	Lower bound of the annual variation concerning the compensation for the electricity injected into the grid	p.u.
ϟ_{Tl}	Lower bound of the annual variation concerning the regulated electricity tariff	p.u.
K_{nl}	Lower bound of the compensation for the electricity injected into the grid	p.u.
K_{Tl}	Lower bound of the regulated electricity tariff	MR$/TWh
V_{max}	Maximum bus voltage	p.u.
V_{min}	Minimum bus voltage	p.u.
Ψ	Number of days per year	Days/year

e	Operational costs	MR$/TWh
PBS	Payback sensitivity	Years^{-1}
μ	Sales tax	p.u.
s	Scalar associated with the CAPEX and OPEX of DG systems	MR$/TWh
$Sizing$	Scalar for estimating the DG system's rated power	p.u.
e'	Scalar of the influence of DG on operational costs	MR$/TWh
SCC	Social cost of carbon	MR$/Mt $CO_{2\text{-eq}}$
M_1	Sufficiently big number	p.u.
M_2	Sufficiently big number	p.u.
t_t	Tax fee	p.u.
ϟ_{nu}	Upper bound of the annual variation concerning the compensation for the electricity injected into the grid	p.u.
ϟ_{Tu}	Upper bound of the annual variation concerning the regulated electricity tariff	p.u.
K_{nu}	Upper bound of the compensation for the electricity injected into the grid	p.u.
K_{Tu}	Upper bound of the regulated electricity tariff	MR$/TWh
β	Weight assigned to penalization	p.u.
r_W	Weighted average cost of capital	p.u.
a	Willingness to consume electricity	MR$/TWh

Parameters	**Description**	**Unit**
$Load_{Curve}(t)$	Characteristic load curve	p.u.
$b(y)$	Degree of satisfaction with the consumed electricity	MR$/TWh²
$B(y)$	Grid investment	MR$
$A_c(y)$	Life cycle emissions of electricity from centralized sources	Mt $CO_{2\text{-eq}}$/TWh
$I_{max}(i,j,y)$	Maximum current of branch (i,j)	p.u.
$p_f(i)$	Power factor of the buses	p.u.
$Bus_{Factor}(i)$	Proportion of active power demand between the buses	p.u.
$Uniform(i,y)$	Random numbers from the uniform probability distribution with bounds [0, 1]	p.u.
$x(i,j)$	Reactance of branch (i,j)	p.u.
$r(i,j)$	Resistance of branch (i,j)	p.u.
$Irrad(t)$	Typical irradiance curve	p.u.

Binary variables	**Description**	**Unit**
$Bin_{Pen}(i,y)$	Penalty variable for preventing multiple DG systems in the same bus	p.u.
$Bin(i,y)$	Variable associated with DG system deployment	p.u.
$Bin_{Inj2}(i,t,y)$	Variable that indicates power injection into the grid (actual prosumers)	p.u.
$Bin_{Inj1}(i,t,y)$	Variable that indicates power injection into the grid (prosumer candidates)	p.u.

Continuous variables	**Description**	**Unit**
$P_d(i,t,y)$	Active power demand	p.u.
$P_g(i,t,y)$	Active power generation from centralized sources at bus i	p.u.
$P_{dg}(i,t,y)$	Active power generation from DG	p.u.
$P_{ij}(i,j,t,y)$	Active power injected at the head of branch (i,j)	p.u.
$n(y)$	Compensation for the electricity injected into the grid	p.u.
$h_2(y)$	Compounded DG self-consumption	p.u.
$E(y)$	Compounded electricity consumption	TWh
$E_{dg}(y)$	Compounded electricity generation from DG	TWh
$ECA(y)$	Consumer and prosumer surplus (economic consumer added)	MR$
$CGWP(y)$	Cost of global warming potential	MR$
$h(i,y)$	DG self-consumption	p.u.
$PMPP(i,y)$	DG system's rated power	kW
$R(y)$	DISCO revenue	MR$
$EVA(y)$	DISCO surplus (economic value added)	MR$

$L(y)$	Energy losses	TWh
$P_{dMax}(y)$	Maximum active power demand of a bus	p.u.
$PBT(i, y)$	Payback time of DG systems	Years
$PEI[EWA(y), CGWP(y)]$	Performance index associated with socioeconomic welfare and environmental issues	MR$
$Prob(i, y)$	Probability of DG system deployment	p.u.
$x(i, j)$	Reactance of branch (i, j)	p.u.
$Q_d(i, t, y)$	Reactive power demand at bus i	p.u.
$Q_g(i, t, y)$	Reactive power generation from centralized sources at bus i	p.u.
$Q_{ij}(i, j, t, y)$	Reactive power injected at the head of branch (i, j)	p.u.
$T(y)$	Regulated electricity tariff	MR$/TWh
$r(i, j)$	Resistance of branch (i, j)	p.u.
$EWA(y)$	Socioeconomic welfare (economic wealth added)	MR$
$I(i, j, t, y)$	Squared current magnitude in branch (i, j)	p.u.
$V(i, t, y)$	Squared voltage magnitude in branch (i, j)	p.u.
$x_3(i, t, y)$	Variable for obtaining power injection into the grid (actual prosumers)	p.u.
$x_4(i, t, y)$	Variable for obtaining power injection into the grid (actual prosumers)	p.u.
$x_1(i, t, y)$	Variable for obtaining power injection into the grid (prosumer candidates)	p.u.
$x_2(i, t, y)$	Variable for obtaining power injection into the grid (prosumer candidates)	p.u.

1 INTRODUCTION

1.1 Motivation

The electric sector presents characteristics that stimulate the formation of natural monopolies, particularly in the distribution and transmission segments [1]. Although the generation and commercialization (wholesale and retail trade) segments are experiencing noticeable competition in developed countries, this is typically not the case for the distribution and transmission segments. Among the characteristics that stimulate the formation of natural monopolies, one can mention the economies of scale that benefit larger companies and the lack of physical space for deploying multiple infrastructures. Consequently, the distribution and transmission segments are usually regulated by the government to protect final consumers from excessive tariffs. The regulation should be effectively planned by the regulatory agency to ensure fairness for all market players and socioeconomic development.

With the support of incentive policies, such as net metering and feed-in-tariff (FIT), and technology cost reduction, the deployment of renewable distributed generation (DG) has been continuously increasing in several countries, particularly photovoltaic (PV) DG, due to its high suitability for small-scale applications (*e.g.*, residential and commercial). DG brings several benefits to the electrical grid and society, such as energy loss reduction [2], mitigation of environmental impacts [3], and possibly investment deferral [4]. However, investment deferral depends on the simultaneity between load and generation. In cases where simultaneity is weak, DG might increase grid reinforcement requirements. Given the typical benefits of DG, electrical systems with unidirectional power flow are in changing process. Globally, PV DG is expected to reach 530 GWp of installed capacity in 2024 [5], which is equivalent to 45% of the US current installed capacity, including all generation sources [6].

Other factors are expected to contribute to DG deployment in the near future. For instance, ESSs, which are becoming more economically feasible, can mitigate the intermittence of DG, enhancing its benefits and the grid's hosting capacity. Similar expectations can be applied for electric vehicles (EVs), which can operate in vehicle-to-grid (V2G) mode when convenient. In addition, advanced market designs and business models are also important to foster the deployment of DG by improving flexibility and profitability. While on-grid ESSs, V2G applications, and advanced business models are currently limited to developed countries [7], they are anticipated to become more popular over time and play a significant role in DG deployment.

Both technical and economic breakthroughs are essential in the context of increasing DG deployment. Nevertheless, regulatory issues are also key. Recent regulatory changes have taken place in the USA, Germany, the UK, and Australia [8]. In general, the idea is to implement enhanced incentives in the early stages to promote DG deployment and then reduce them as the installed capacity becomes substantial (*e.g.*, a decrease in FIT rates in Germany [8]). Similar trends are occurring in Brazil through the implementation of the Ordinary Law 14300/2022 (OL).

In 2012, the Brazilian Electricity Regulatory Agency (ANEEL) published the Normative Resolution (NR) 482 [1] [9], which was the first specific regulation of on-grid renewable DG in Brazil for residential customers. In order to foster the DG installed capacity, the NR 482 implemented the net metering policy, which ensures 100% compensation for the electricity injected into the grid for prosumers. In 2015, the NR 687 was published [10], consisting of a review of the previous resolution. As a result, several modifications were implemented, such as the definition of micro and mini-generation and new investment modalities (*e.g.*, shared generation). However, the NR 687 maintained the net metering scheme. Consequently, the DG installed capacity has been increasing substantially in Brazil, reaching more than 18 GWp in Mar/2023.

The continuous deployment of DG has stimulated avid discussions concerning regulatory changes since 2019, when ANEEL published the Public Hearing 25/2019 (PH) [11], consisting of five compensation alternatives besides the net metering policy. These alternatives present a different compensation percentage based on the Brazilian tariff structure, as illustrated in Figure 1.1. The acronym TE in Figure 1.1 regards the electricity tariff, *i.e.*, only the cost of purchasing electricity. In contrast, TUSD concerns the distribution system tariff, *i.e.*, the infrastructure cost for electricity transport. Both TE and TUSD exhibit associated taxes. Grid A gathers the unmanageable components, *i.e.*, components that the company does not control (*e.g.*, transmission costs), whereas Grid B includes the manageable components, which the company controls (*e.g.*, employee costs). The PH was heavily criticized by agents associated with the DG supply chain due to its relatively low compensation and sudden proposed changes. Consequently, it was not approved.

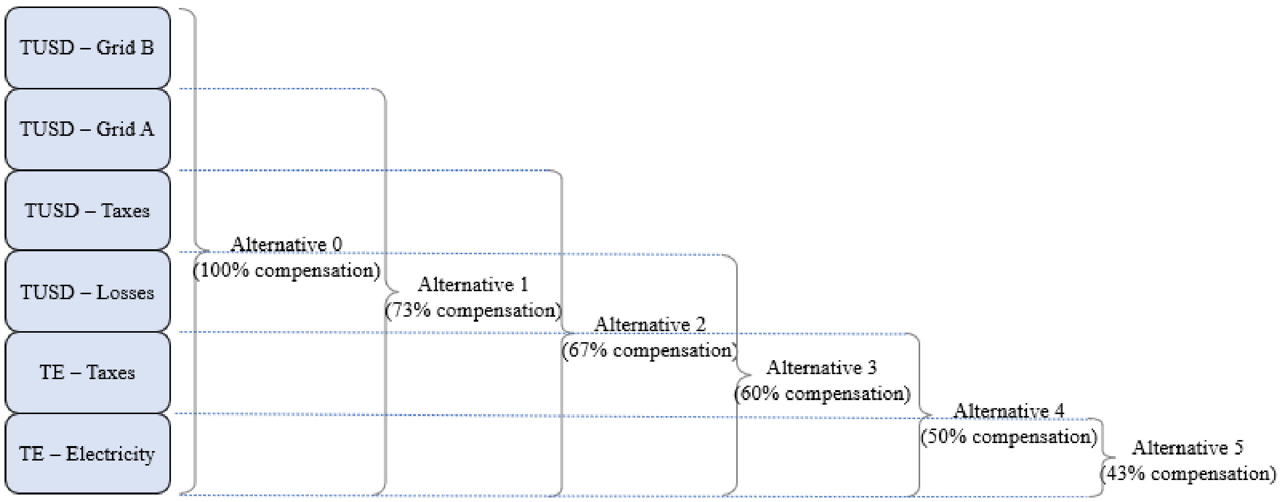

Figure 1.1. PH alternatives [2] (data from [11]).

[1] All mentioned regulatory frameworks (NR 482, NR 687, PH, and OL) are valid for all DG sources.
[2] Average values for the whole country. The compensation might vary slightly depending on the concession area.

After the PH disapproval, the OL was created and approved by Congress in Jan/2022 [12]. Its main idea is to maintain 100% compensation (net metering) until 2045 for prosumers who requested access from the distribution company (DISCO) within one year after the law implementation, *i.e.*, until Jan/2023. However, the compensation for prosumers who request access after Jan/2023 decreases according to Figure 1.2. The OL concerns a middle ground between the net metering scheme and the PH proposals since the compensation decreases over time, implying a smoother transition. After 2030, the National Council for Energy Policies (CNPE) will define the compensation rules by calculating all the costs and benefits of DG, including improvements in generation, transmission, distribution, and energy losses. ANEEL should have published such rules until Jun/2023, but this process is still ongoing as of Dec/2023.

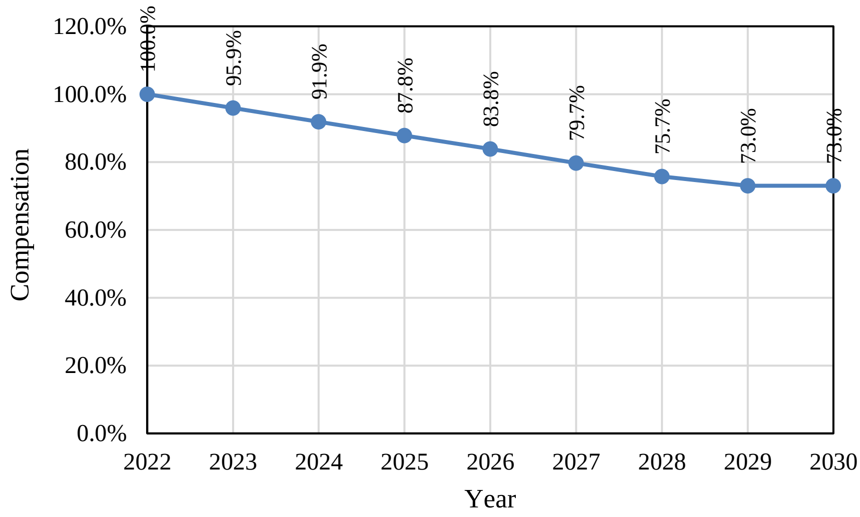

Figure 1.2. OL compensation (data from [12]).

A timeline of the main events associated with DG regulation in Brazil is illustrated in Figure 1.3. It is emphasized that Figure 1.3 is highly simplified, as there were also other associated events. More information is available in Pereira [13].

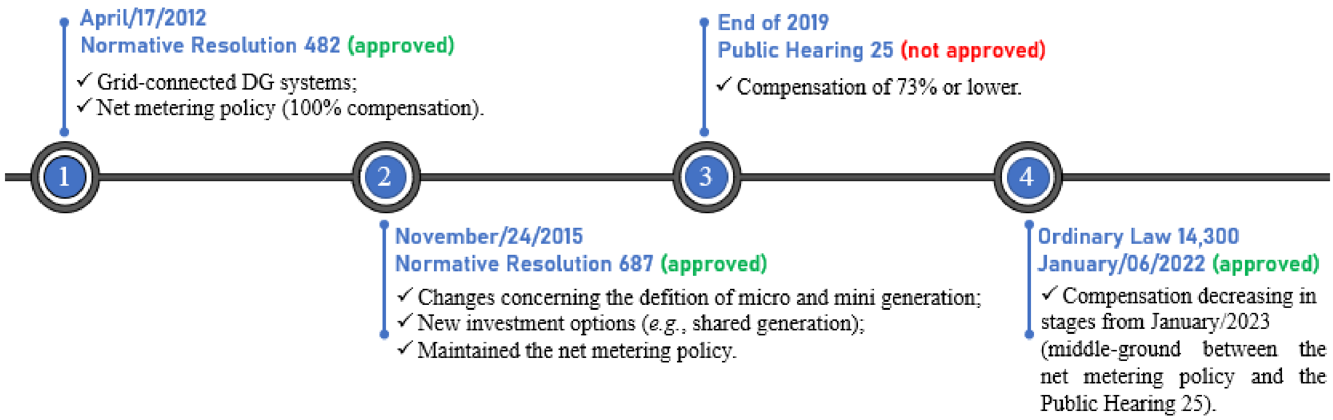

Figure 1.3. Simplified timeline of DG regulation in Brazil.

The OL aims to mitigate tariff raises induced by DG integration. Hence, it is seen as a fairer policy than the net metering scheme from the perspective of conventional consumers who are unable (or do not wish) to invest in DG systems. While the idea of implementing the OL is legitimate, several questions and concerns naturally arise for two main reasons: (*i*) it is not a trivial task to propose a fair regulation for all market agents (consumers, prosumers, DISCOs, and government), and (*ii*) regulatory changes have massive implications in several aspects (economic, social, environmental, political, and technical). Therefore, assessing these two issues is extremely important before implementing regulatory changes. Moreover, although DG profitability and DISCOs' revenues were taken into account to design the OL, it is debatable whether a robust and holistic enough methodology has been applied and if the achieved trade-off is satisfactory.

Generally, prosumers have limited choices concerning the surplus electricity from DG, as it can only be traded with the DISCO by injecting the surplus electricity into the grid (*e.g.*, the current Brazilian regulatory framework). However, prosumers are gradually becoming more empowered through the spreading of consumer-centric electricity markets [14], which opens up several opportunities for the commercialization of electricity. Conventional consumers can also significantly benefit from such markets by choosing their electricity provider and possibly reducing costs. For instance, the Hawaii Public Utilities Commission implemented a community-based renewable energy program to expand access to the economic, environmental, and social benefits of renewable energy [15]. Furthermore, the program seeks project opportunities dedicated to low and moderate-income customers.

Consumer-centric electricity markets, such as community-based markets (CBMs), are expected to be essential market designs in the future [14]. However, they are not expected to replace conventional markets entirely and will still require a certain level of regulation. Given this whole background, this thesis evaluates regulatory issues associated with DERs and CBMs.

The optimized tariff (TAROT) is a regulated electricity market model that aims to represent the market objectively. It concerns a simplified version of tariff review procedures carried out by ANEEL, given that they are complicated. Moreover, unlike the official tariff review procedures, the TAROT represents consumers, allowing more integral analyses. Therefore, the TAROT has been widely applied by researchers [16], [17], [18], [19], [20], [21] (see Chapter 2 for more details). Although the model has historically been applied in a stand-alone manner, its combination with other techniques, such as the Bass diffusion model (BDM), life cycle assessment (LCA), and multi-objective optimization (MOO), is promising for holistic and in-depth analyses of the regulated electricity market. It is expected that this thesis sheds light on the effectiveness of the TAROT when integrating multiple techniques, possibly contributing to the development of the topic.

For better contextualization, a discussion on the Brazilian regulatory framework concerning tariff formation and structure is conducted below. The regulated electricity tariff is defined by ANEEL through the tariff review procedures (PRORET). The methodology for calculating the tariffs is similar throughout the country, but the tariffs differ in each concession area. In short, tariffs are calculated through the required revenue to cover all the DISCO costs, including operational and energy loss costs, depreciation, taxes, tributes, capital yield, etc. Moreover, the tariff is separated into components “A” and “B”. Component “A” gathers the unmanageable costs, *i.e.*, those that DISCOs do not control, whereas component “B” gathers the manageable costs, which DISCOs control. Such components are detailed in Table 1.1.

Regarding component “B”, ANEEL applies an incentive-based regulation that encourages the efficient operation of DISCOs. The incentive is given through the “X” factor, which subtracts the tariff in the tariff review. The better the DISCO efficiency, the lower the “X” factor. It is noteworthy that the DISCO keeps a portion of the efficiency gain while the other portion is passed on to consumers through a reduced tariff. The detailed calculation of components “A” and “B” and the “X” factor is outside the scope of this thesis. As previously mentioned, the TAROT concerns a simplified version of the PRORET that allows for more straightforward market assessments. Hence, one can understand the models proposed in this thesis without an in-depth understanding of the PRORET.

TABLE 1.1. COMPONENTS OF THE REGULATED ELECTRICITY TARIFF [22].

Component “A”	Component “B”
• Electricity purchase and transmission costs; • Sector charges.	• Operational costs; • Depreciation quota; • Capital yield; • Other revenues.

1.2 Objectives and contributions

This thesis aims to answer five main research questions (RQs):

RQ1: How has the COVID-19 pandemic impacted the regulated electricity market? How to create corrective measures to mitigate the impact of future crises?;

RQ2: How to model the regulated electricity market in the context of increasing penetration of DG and ESSs?

RQ3: How to integrate multiple techniques to allow a holistic assessment of the regulated electricity market in the context of increasing DG penetration? How to propose optimal and holistic regulatory frameworks in the same context?

RQ4: How to propose a holistic optimization model that assumes the co-existence between conventional markets and CBMs?

RQ5: How to propose an optimization model that accounts for the electric grid and the random locational aspect of DG systems?

The following objectives were established to answer the RQs:

(*i*) Apply the conventional TAROT model to analyze the potential impacts of the COVID-19 pandemic on the Brazilian regulated electricity market and propose corrective public policies;

(*ii*) Adapt the TAROT and BDM to the context of DG, ESSs, and time-of-use (TOU) rates to assess multiple phenomena associated with the regulated electricity market, namely: (*i*) evaluate the long-term consequences of increasing DERs penetration levels in the market, (*ii*) analyze the pros and cons of promoting investments in ESSs, (*iii*) assess how the implementation of public policies can foster the integration of ESSs, and (*iv*) investigate means of promoting energy shifting;

(*iii*) Use the TAROT, BDM, and LCA to holistically analyze the impacts of the OL in terms of socioeconomic welfare, regulated electricity tariff, and global warming potential (GWP);

(*iv*) Combine the TAROT, BDM, and LCA into a MOO approach for obtaining holistic and optimal regulatory frameworks for DG. Then, compare the optimal solutions to the OL to evaluate whether the law achieved a satisfactory trade-off;

(*v*) Extend the proposed model by assuming the co-existence between conventional markets and CBMs and evaluate the potential of implementing CBMs in Brazil.

(*vi*) Propose an iterative scenario-based bi-level optimization problem based on inner and outer convergence loops, in which the former is associated with the convergence of the upper and lower optimization levels (regulatory and operational sub-problems, respectively), whereas the latter represents scenario variation.

It is expected that the models proposed in this thesis and the in-depth discussions can assist regulatory agencies when regulatory changes are envisaged, given the lack of robust and holistic regulatory models in the literature. Moreover, this thesis can also be valuable for researchers and government institutions linked to DG, socioeconomic, or environmental issues and contribute to the faster dissemination of CBMs.

1.3 Related publications

The research conducted during this thesis proposal resulted in the publication of some related papers, as follows:

(Paper *a*) - V. B. F. Costa, B. D. Bonatto, L. C. Pereira, and P. F. Silva, "Analysis of the impact of COVID-19 pandemic on the Brazilian distribution electricity market based on a socioeconomic regulatory model," *International Journal of Electrical Power & Energy Systems*, vol. 132, p. 107172, Nov. 2021, doi: 10.1016/j.ijepes.2021.107172.

(Paper *b*) - V. B. F. Costa, L. C. Pereira, J. V. B. Andrade, and B. D. Bonatto, "Future assessment of the impact of the COVID-19 pandemic on the electricity market based on a stochastic socioeconomic model," *Appl Energy*, vol. 313, p. 118848, May 2022, doi: 10.1016/J.APENERGY.2022.118848.

(Paper *c*) - V. B. F. Costa, B. D. Bonatto, and P. F. Silva, "Optimizing Brazil's regulated electricity market in the context of time-of-use rates and prosumers with energy storage systems," *Util Policy*, vol. 79, p. 101441, Dec. 2022, doi: 10.1016/J.JUP.2022.101441.

(Paper *d*) - V. Costa, B. Bonatto, A. Zambroni, P. Ribeiro, M. Castilla, and L. Arango, "Renewables with Energy Storage: A Time-series Socioeconomic Model for Business and Welfare Analysis," *J Energy Storage*, p. 103659, Nov. 2021, doi: 10.1016/j.est.2021.103659.

(Paper *e*) - V. B. F. da Costa and B. D. Bonatto, "Cutting-edge public policy proposal to maximize the long-term benefits of distributed energy resources," *Renew Energy*, vol. 203, pp. 357–372, Feb. 2023, doi: 10.1016/J.RENENE.2022.12.045.

(Paper *f*) - V. B. F. Costa *et al.*, "Socioeconomic and environmental consequences of a new law for regulating distributed generation in Brazil: A holistic assessment," *Energy Policy*, vol. 169, p. 113176, Oct. 2022, doi: 10.1016/J.ENPOL.2022.113176.

(Paper *g*) - V. Costa, R. Capaz, and B. Bonatto, "Small steps towards energy poverty mitigation: Life Cycle Assessment and economic feasibility analysis of a photovoltaic and battery system in a Brazilian indigenous community," *Renewable and Sustainable Energy Reviews (in press)*, Mar. 2023, https://doi.org/10.1016/j.rser.2023.113266.

Some articles that have not been published yet should be mentioned:

(Paper *h*) - V. Costa *et al.*, "Proposal of an advanced regulatory framework for distributed generation considering socioeconomic and environmental indicators: a multi-objective optimization approach," Mar. 2023, doi: 10.5281/ZENODO.7708858.

(Paper *i*) - V. Costa *et al.*, "A holistic approach to regulating community-based electricity markets: integrating socioeconomic and environmental objectives through multi-objective optimization," Mar. 2023, doi: 10.5281/ZENODO.7752971.

The relationships between this thesis' objectives and the published papers are presented in Table 1.2. It is noteworthy that Paper *g* conducts an LCA in notable detail. Hence, it is the foundation for this thesis' environmental analyses.

TABLE 1.2. RELATIONSHIP BETWEEN THE THESIS' OBJECTIVES AND THE PUBLISHED PAPERS.

Objective discussed in Section 1.2	Published papers
(*i*)	Papers *a*, *b*
(*ii*)	Papers *c*, *d*, *e*

(*iii*)	Paper *f*, *g*
(*iv*)	Papers *g*, *h*
(*v*)	Papers *g*, *i*

1.4 Thesis structure

In addition to this introductory chapter, this thesis is structured as follows: Chapter 2 carries out a literature review on the applied techniques/approaches, *i.e.*, TAROT, BDM, LCA, MOO, holistic regulatory analyses, and bi-level optimization. Chapter 3 presents the conventional TAROT model and its application in the context of the COVID-19 pandemic (Section 3.4). Chapter 4 adapts the TAROT model to the context of DERs integration and performs static and time-dependent case studies (Sections 4.3 and 4.5, respectively). Chapter 5 presents a holistic approach to analyzing the impacts of the OL (Section 5.2) and proposes a MOO problem for obtaining optimal regulatory framework solutions assuming the absence and presence of CBMs (Sections 5.3 and 5.4, respectively). Chapter 6 introduces the iterative scenario-based bi-level optimization problem to account for the electric grid and the random locational aspect of DG systems. Finally, Chapters 7, 8, 9, and 10 exhibit philosophical reflections, research limitations, conclusions, and data used in this thesis, respectively.

For ease of view, a summary of the techniques/models, purposes, and target group of Chapters 2 to 6 is presented in Table 1.3.

TABLE 1.3. SUMMARY OF THE TECHNIQUES/MODELS, PURPOSES, AND TARGET GROUP OF CHAPTERS 2 TO 6.

Chapter	Techniques/ models	Purposes	Target group
2 - Literature review.	• TAROT *; • BDM *; • LCA *; • MOO *; • Holistic regulatory analysis *; • Bi-level optimization *. * Only the associated ideas and not the model/math itself.	• Discuss the general idea, advantages, and disadvantages of each model; • Present and contextualize the main works found that apply the models; • Evaluate how the methodologies proposed in this thesis differ from those found in the literature, thus specifying the research gap tackled herein.	• Readers who are not yet familiar with the models but seek to understand the basics; • Readers seeking an overview of associated literature;

3 - The conventional TAROT model.	TAROT	• Present the conventional TAROT model formerly proposed by Arango *et al.* [16], which does not explicitly include DERs; • Achieve objective (*i*) and answer RQ1.	• Readers seeking to learn the conventional TAROT model (math), which should be the first step towards developing more advanced regulatory models; • Readers seeking a practical application of the TAROT (COVID-19) to understand its usefulness; • Readers interested in an analysis of the potential impact of the COVID-19 pandemic on the regulated electricity market.
4 - The TAROT model in the context of DERs integration.	• TAROT; • BDM.	Achieve objective (*ii*) and Answer RQ2;	• Readers interested in extensions of the TAROT. Although this chapter presents an extension, the model is mathematically simple and does not use optimization techniques (mathematical programming), thus being easy to follow; • Readers seeking to learn the BDM proposed by Beck (math) [23]. This model is used for forecasting the total DER installed capacity and therefore does not account for the locational aspect of DER integration; • Readers interested in the effects of DERs on the regulated market.
5 - The TAROT model from a holistic perspective.	• TAROT; • BDM; • LCA; • MOO; • Holistic regulatory analysis.	Achieve objectives (*iii*), (*iv*), and (*v*) and answer RQ3 and RQ4;	• Readers interested in the implications of the OL (current Brazilian regulatory framework for DG); • Readers seeking to research how environmental and energy poverty aspects can be integrated into regulatory decision-making; • Readers interested in advanced regulatory models used for market optimization. This chapter represents a middle ground in terms of complexity since it applies optimization techniques. In any case, understanding the basic ideas, results, and associated discussions does not require previous knowledge of optimization techniques; • Readers interested in the effects of DG on the regulated market. Unlike Chapter 4, this chapter does not address ESSs; • Readers interested in optimization techniques (scalarization MOO using mathematical programming).
6 - Bridging the gap between	• TAROT; • BDM; • LCA;	Achieve objective (*vi*) and answer RQ5;	• Readers interested in the consequences of detailed energy loss modeling on the regulated market;

regulatory and operational aspects	• Bi-level optimization.		• Readers seeking to research how technical issues (electric grid) and regulatory issues can be considered simultaneously in decision-making; • Readers interested in the effects of DG on the regulated market. Unlike Chapter 4, this chapter does not address ESSs; • Readers interested in optimization techniques (iterative bi-level optimization using mathematical programming); • Readers interested in advanced regulatory models used for market optimization. This chapter is the most complex. In any case, understanding the basic ideas, results, and associated discussions does not require previous knowledge of optimization techniques; • Readers interested in the locational/time-dependent BDM proposed by Abud *et al.* [24] and adapted herein to enable optimization algorithms; • Readers interested in optimal power flow models (branch flow model).

2 LITERATURE REVIEW

2.1 Optimized tariff model

The TAROT is a socioeconomic regulated electricity market model proposed by Arango *et al.* [16]. It represents consumers, DISCOs, and society based on input data from official tariff review procedures. As outputs, the model provides the market players' surpluses, *i.e.*, their benefit from selling or purchasing electricity. Such surpluses can be used to analyze the consequences of multiple phenomena on the regulated electricity market. The model's basic structure is discussed in detail in Chapter 3.

State-of-the-art publications have demonstrated that the TAROT is highly effective in distinct modeling contexts due to its flexibility. Publications include, for instance, analyses of the implications of the COVID-19 pandemic on the market (Papers *a*, *b*), evaluations of the deployment of ESSs and time-of-use (TOU) rates (Papers *c*, *d*, *e*), a holistic assessment of the consequences of the OL (Paper *f*), an assessment of fair social electricity tariffs [17], an examination of the influence of power quality on the market [18], an aggregated economic analysis of the Brazilian DISCOs [19], an electricity market risk assessment [20], and an evaluation of the implications of power theft [21].

Maciel *et al.* [17] addressed the electrical energy social tariff (TSEE), which is a Brazilian public policy aimed at favoring low-income consumers through tariff discounts. The TSEE guarantees cumulative discounts of 65%, 40%, and 10% for electricity consumption over 30, 70, and 120 kWh, respectively, and the policy assists more than 12 million families. According to the authors, the overall discount is only around R$ 20 per family. Thus, the TSEE's effectiveness as a stand-alone policy is limited. As an alternative solution to mitigate energy poverty, the authors used the TAROT to propose tax exemptions, which proved to be effective. Although this thesis does not address the TSEE, it also evaluates opportunities to mitigate energy poverty through CBM implementation. The proposal of distinct solutions is expected to contribute concurrently to mitigating the problem.

Arango *et al.* [18] proposed an extension of the TAROT model covering power quality issues. The authors evaluated a scheme in which DISCOs must compensate consumers for unsatisfactory power quality. This approach ensures that DISCOs seek to invest properly in power quality and that consumers only pay for the quality level they receive. However, such an extension is not considered here due to distinct work emphasis.

Cortez *et al.* [19] applied the conventional TAROT to analyze the performance of 52 Brazilian DISCOs. The authors indicated that regulated electricity tariffs varied from 0.367 to 0.828 MR$/TWh, with an average of 0.547 MR$/TWh. Such tariffs were mostly excessive, as only 12% of DISCOs presented financial losses, 18% were financially stable, and 69% presented gains far above the envisaged. The authors estimated that tariff decreases of around 4% were reasonable. Furthermore, only 12% of DISCOs invested properly in the grid, 14% under-invested, and 74% over-invested. Over-investments are not particularly worrisome from the DISCOs' perspective since the associated costs are passed on to consumers in the current regulatory model. The work conducted by Cortez *et al.* highlights the effectiveness of the TAROT in providing overviews of the regulated market that can be used for better managerial decision-making. This is particularly important due to the intricacy of the current regulatory processes carried out by ANEEL (PRORET).

Cortez *et al.* [20] proposed a stochastic TAROT model to account for risks associated with electricity consumption and the DISCO's operational costs. The results demonstrated that the DISCOs are very sensitive to risks. Papers *b* and *e* also conducted stochastic simulations of the regulated electricity market using similar techniques to Cortez *et al.* The authors concluded that while stochastic analyses are important, the lack of a large historical series is a significant bottleneck in Brazil. This thesis introduces a scenario-based optimization problem in Chapter 6 that requires limited historical data (basically the same data as the conventional BDM) to account for the random locational aspect of DG systems.

Arango *et al.* [21] proposed an extension of the TAROT model covering power theft, which can be used to estimate the influence of power theft on the DISCO's revenue and costs, and the regulated electricity tariff. The authors separate electricity consumption into billed and unbilled electricity. Although this thesis' work emphasis differs from Arango *et al.*, the separation of electricity consumption into components is conducted similarly. Specifically, generation from DG is separated into self-consumption, injection into the grid, and local commercialization in the CBM. This approach enables analyzing the consequences of distinct prosumer behaviors.

As demonstrated in the several works that apply the TAROT, its application is beneficial since (*i*) it is characterized as a socioeconomic model rather than merely economic since it takes into account the quality of life added by electricity consumption, (*ii*) it can be adapted to several contexts such as the one evaluated in this thesis (regulatory context of DERs), (*iii*) it considers the interests of consumers, prosumers, and DISCOs, (*iv*) its equations are mathematically simple, ensuring low computational effort, and (*v*) it can be combined with other models or techniques (*e.g.*, BDM) for enhanced analysis. As the main disadvantage of the model, one should mention its low level of detail since consumers are typically aggregated. However, it is also possible to apply the model in a decentralized manner, as demonstrated in Chapter 6.

2.2 Bass diffusion model

The BDM is a forecasting model proposed by Frank Bass [25] and is widely applied to model the commercialization of new technologies introduced into the market. For instance, it has been applied to model the commercialization of vehicles [26], computers [27], cell phones [28], and ESSs (Papers *d*, *e*).

In the context of DG integration, the application of the BDM is widespread, as it has been applied by ANEEL [29], National Renewable Energy Laboratory (NREL) [30], [31], and academic researchers (Papers *d*, *e*, *f*), [32], [33].

NREL developed the SolarDS model in 2009, which is a market penetration model that simulates the potential adoption of distributed PV systems based on the BDM [30]. The SolarDS model has grown to be used in a number of prominent analyses and influenced the design of other new tools [31]. In 2016, the model was reformulated and renamed dGEN. Developing dGEN remains an ongoing project in which new features are added as needed. Given the popularity of the BDM for estimating the adoption of distributed PV systems, ANEEL applied it in 2017 [29], contributing to upcoming research in the Brazilian context [32], [33], [24], [34], [35].

Santos *et al.* [32] applied the BDM and system dynamics technique to develop a diffusion model for low-voltage DG systems, taking into account economic, management, political, social, and technical aspects. Such an all-encompassing model can be used for detailed studies on the influence of each aspect on DG diffusion. However, a simpler diffusion model is assumed in this thesis, based only on economic aspects for three main reasons: (*i*) economic aspects are the most important [32], (*ii*) the analyzed problem is conceived from the perspective of the regulatory agency, which has limited or no influence on several aspects (*e.g.*, the regulatory agency cannot increase the efficiency of PV modules), and (*iii*) parameter tunning is very intricate in the model proposed by Santos *et al.* [32].

Silva *et al.* [33] applied the BDM to predict the adoption of distributed PV systems, focusing on developing a detailed approach for estimating market potential. The authors argue that ANEEL's official projections overestimate DG diffusion since the agency considered parameters from the USA. Consequently, using actual data from the study's location is essential to ensure proper estimations, as done so in this thesis.

Abud *et al.* [24] also applied the BDM to predict the adoption of distributed PV systems. The model was applied for each consumer unit to estimate the individual probabilities of installing distributed PV systems. Then, based on the obtained probabilities, a Monte Carlo simulation was performed using the software OpenDSS to assess the systems' impacts on the grid over time and anticipate potential technical violations. In turn, this thesis applies an aggregated BDM (without individual calculations) in Chapters 4 and 5. However, a similar approach to that proposed by Abud *et al.* (scenario-based and locational) is introduced in Chapter 6.

Rao *et al.* [36] conduct a review of technology diffusion models focusing on renewable generation. The authors highlight the importance of policies in driving the uptake of emerging renewable generation technologies. Therefore, models should explicitly establish a relationship between policies and diffusion rates.

In this thesis, such a relationship is established through the payback time of investing in DG systems, as proposed by Beck [23].

Xia *et al.* [37] proposed a generalization of the BDM to model the diffusion of fuel cell electric vehicles (FCEVs) in China, taking into account the levelized cost of driving and the number of hydrogen refueling stations. The model proposed by the authors draws attention to the BDM's flexibility, as it can be adapted or extended to different contexts. However, the adoption of FCEVs is currently very incipient. Hence, some parameters are difficult to estimate due to a lack of historical series. In turn, this thesis uses the BDM to model the diffusion of distributed PV systems, which already have reasonable historical series, facilitating parameter estimation.

Laws *et al.* [38] addressed the utility death spiral problem and the impact of tariff structures on the adoption of distributed PV and storage systems. Similar to this thesis, the authors consider economic aspects to model technology diffusion, but the net present value (NPV) is assumed instead of the payback time. The payback time is assumed here since the NPV varies widely depending on the systems' scale. Moreover, data from ANEEL concerning the sensitivity to economic variations is also associated with the payback time (payback sensitivity parameter P_{BS}). The model proposed by Laws *et al.* indicates significant tariff raises due to the increasing penetration of DERs, which may induce the death spiral process if the market is not regulated satisfactorily. Similar outcomes were reached in this thesis.

Iglesias *et al.* [34] applied the BDM to evaluate the consequences of the OL compared to the net metering policy. Thus, the study has a similar work emphasis to this thesis. However, the authors focused on economic aspects (*e.g.*, LCOE and cost-benefit index), whereas this thesis aims to provide a more holistic overview of regulatory impacts. Iglesias *et al.* suggested that the OL is substantially detrimental to prosumers but beneficial to DISCOs. Such a trade-off is also analyzed here.

Bitencourt *et al.* [35] applied the BDM to assess the influence of several public policies on EV diffusion in Brazil (*e.g.*, reduction in taxes and carbon taxation). Public policies are easily representable in terms of payback time, which makes the BDM highly appealing for these types of applications. A similar approach is used in this thesis to express the relationship between the regulatory agency's decision-making and the payback time of investing in DG systems.

She *et al.* [39] applied an extension of the BDM to analyze wind power development in China. Such an extension considers the effect of shock or surprise on technology diffusion. The shock effect occurs when new information is available and can be understood as a transient phenomenon on the diffusion curve, which may present different shapes (*e.g.*, exponential, rectangular, or a combination) and assist or jeopardize technology diffusion. For instance, the announcement that the OL would be implemented in Jan/2023 might have fostered DG integration in late 2022 and reduced it in early 2023. On the other hand, this thesis does not consider the shock effect. Nevertheless, integrating the shock effect into the modeling might be a valuable future work opportunity, as further detailed in Section 7.1.

In summary, the literature review highlights that the application of the BDM is advantageous since (*i*) it requires limited historical data for accurate results [40], (*ii*) it assumes the technology payback time as an input parameter [3], making it an appealing tool for regulatory studies, and (*iii*) it considers the stagnation stage of technology commercialization, which is essential in long-term assessments such as the ones conducted in this thesis.

2.3 Life cycle assessment

LCA is among the most applied methods for quantifying environmental impacts. It has been applied in numerous studies of renewable electricity generation, especially PV (Papers *f*, *g*), [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55]. The application of LCA is beneficial since (*i*) it is standardized by the International Organisation for Standardisation (ISO) 14040 and 14044 [56], ensuring consistency, (*ii*) it takes into account the whole product's life cycle, which is essential to quantify the environmental impacts of renewable generation properly, and (*iii*) it enables accurate assessments adapted to each region and context with typically linear calculations.

ISO defines four main phases for performing an LCA [56], as follows:

1) Goal and scope definition. For clarity and transparency, the scope should be thoroughly described beforehand since different assumptions may change the assessment results;

2) Life cycle inventory (LCI). At this stage, the data required for the assessment should be gathered, which can be done through public or commercial datasets, previous studies or publications, own experience, or a combination of the three;

3) Life cycle impact assessment (LCIA). At this stage, the product's environmental impact is calculated based on an LCIA method. Several recognized methods classify and calculate environmental impacts differently. Hence, the LCIA method should be selected accordingly (usually at phase 1), depending on the application;

4) Interpretation. Finally, conclusions are drawn at stage four. Additionally, the adequacy of the results should be assessed for potential misconceptions throughout the study, such as inaccurate assumptions or background data [57].

2.4 Holistic regulatory analyses

In a MOO problem, the Pareto frontier is the set of all Pareto efficient solutions or non-dominated solutions, as illustrated in Figure 2.1. In the Pareto frontier, no objective can be improved without

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[3] There are some variations of the BDM. The model applied in this thesis assumes the payback time as an input parameter as proposed by Beck [23].

deteriorating at least one of the other objectives. Consequently, the decision-maker should select a solution of the Pareto frontier to base their decision. The solution to be selected is usually the knee point, which is the solution with the minimum distance to the utopia point (an ideal point that optimizes all objectives, usually infeasible). The knee point is generally selected since it provides the best trade-off among objectives, in which the improvement of one objective will result in the serious degradation of at least one other objective [58]. Figure 1.4 illustrates the knee point assuming the Euclidian distance but this concept can be extended to other distances (Manhattan and Chebyshev) generating knee sets, as further discussed in Chapter 5.

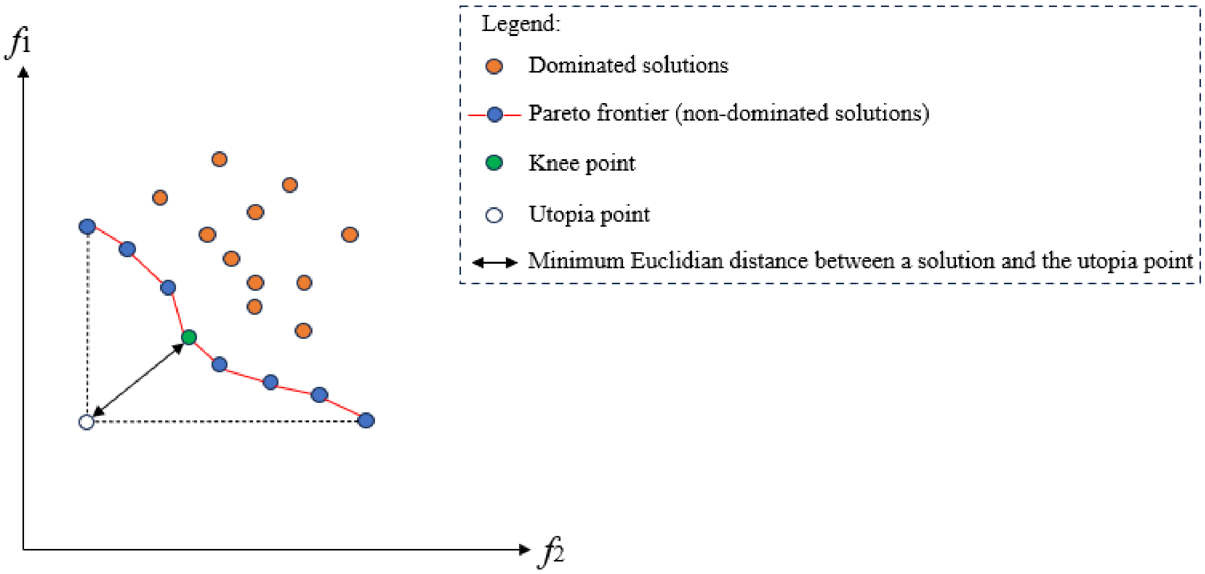

Figure 2.1. Illustrative example of the main concepts of MOO, assuming minimization for f_1 and f_2.

MOO has substantial practical importance since real-world problems typically present multiple conflicting objectives (trade-offs) [59]. Classical MOO methods are classified as scalarization and Pareto methods [60]. In scalarization methods, the MOO is converted into a single objective optimization, whereas in Pareto methods, evolutionary algorithms are used to search for dominated and non-dominated solutions, thereby leading to the obtention of the Pareto frontier. In the context of electricity generation, MOO is extensively applied since different sources typically present a series of advantages and disadvantages [61], [62], [63]. Moreover, regulatory changes concerning DG are never beneficial from every point of view since the market players' interests are distinct (Paper *f*).

The assessment of DG penetration in power systems requires the study of their integration considering different aspects. Commonly, the literature has been focused on studying the impact of increasing DG penetration considering the socioeconomic welfare, electricity tariff, or GWP aspects, as shown in Table 2.1. It has been verified that the impact of DG on electricity tariffs is extensively studied, while environmental and socioeconomic aspects are not as thoroughly assessed. Jointly evaluating these three aspects is very rare in the literature. Heideier *et al.* [64] reached similar conclusions, stating that studies addressing the effects of DG diffusion not only in the economic dimension but in other dimensions, including environmental and social aspects, are rare. It was also verified that there is a lack of analytical models or non-empirical analyses, particularly optimization approaches. No documents were found that consider socio-economic welfare, electricity tariff, and GWP aspects and propose an optimal regulatory framework for DG. Therefore, the literature review demonstrates that this thesis tackles an important research gap as it approaches the problem from a holistic and optimal perspective. It is noteworthy that GWP is presented in Table 2.1 since it is a commonly addressed impact category. However, Castro *et al.* [65] and Millar *et al.* [66] also address air quality issues (SO_2 and NO_x emissions).

TABLE 2.1. LITERATURE REVIEW OF DOCUMENTS FOCUSED ON DISTRIBUTED GENERATION.

	Aspects assessed in detail			Methodology	
	Socioeconomic welfare	Electricity tariff	Global warming potential	Analytical model (non-empirical analyses)	Optimization approach (mathematical programming or meta-heuristic techniques)
Heideier *et al.* [64]	✓ [a]	✓	✓	✓	
ANEEL [29]		✓		✓	
Castro *et al.* [65]		✓	✓		
Millar [66]		✓	✓	✓	
Pérez-Arriaga *et al.* [67]		✓			
Cossent *et al.* [68]		✓			
Frías *et al.* [69]		✓			
Lopes *et al.* [70]			✓		
Hinz *et al.* [71]		✓		✓	
Cossent *et al.* [72]		✓			
Ruiz-Romero *et al.* [73]		✓			
Ruester *et al.* [74]		✓			

[a] The social indicator is assumed to be job creation.

Moreover, although there is already well-established research on modeling electricity commercialization in CBMs [14], [75], [76], [77], there is a lack of integrated approaches. Studies typically assume that CBMs are independent of conventional markets and the regulatory framework. Therefore, it is important to develop means for both markets to co-exist in harmony, along with advanced models that capture the influence of regulatory frameworks on CBMs. Furthermore, the available literature focuses on cost minimization. Consequently, more work is required on other aspects, such as social and environmental ones. In conclusion, this thesis also fills an important research gap concerning CBMs.

2.5 Bi-level optimization

Bi-level programming is applied in hierarchical problems, in which the upper and lower levels have their own mathematical models [78]. The solution of the lower-level sub-problem is fed back to the upper-level, and the upper-level conforms to the global optimal. While bi-level optimization problems are relatively common in DG applications, as shown in Table 2.2, most studies are related to optimal distributed energy resources (DERs) siting and/or sizing and expansion planning. Cervilla *et al.* [79], Pediaditis *et al.* [80], and Hoarau *et al.* [81] address tariff design as the upper-level sub-problem. Thus, such works are reasonably related to this thesis. Nonetheless, they assume prosumer actions (investments and consumption) as the lower-level sub-problem. In turn, this thesis integrates the decision-making of both the regulatory agency and prosumer candidates on the upper-level sub-problem. This approach ensures that the feedback mechanism between the regulatory agency's decision-making and the uptake of DG is strongly bounded. Moreover, it establishes a satisfactory convergence process since the upper-level sub-problem works with reasonable information on DG uptake.

As per Table 1, concerning solution methods, two typical approaches in the literature are: (*i*) applying mathematical programming with equilibrium constraints (MPEC) and using Karush-Kuhn-Tucker (KKT) conditions to convert the bi-level optimization problem into a single-level problem, which can be solved by MILP and MIQP solvers; (*ii*) applying an iterative method (IM) in which the upper and lower-level problems are solved recursively until a stopping criterion is met. The latter approach is considered in Chapter 6, given the cascaded structure of the sub-problems and that the lower-level subproblem can be linearized and decoupled in time. Inner and outer convergence loops are envisaged, in which the former is associated with the convergence of the upper and lower levels for a specific scenario, whereas the latter represents scenario variation. Liu *et al.* [82] also proposed a bi-level optimization approach with inner and outer convergence loops. However, in a completely different context (expansion planning). No work that applies a similar optimization method to that of Chapter 6 (iterative bi-level scenario-based) was found in a regulatory context. Consequently, Chapter 6 also fills an important research gap, as modeling the bounded characteristics between regulatory and operational aspects is essential for enhanced managerial decision-making.

TABLE 2.2. OVERVIEW OF BI-LEVEL FORMULATIONS IN DG APPLICATIONS.

Article	Upper-level	Lower-level	Solution method and problem class
Liu *et al.* [78]	Siting and sizing of DG and electric vehicle (EV) charging stations	Active management strategies	PSO
Cervilla *et al.* [79]	Tariff design	Investments in PV generation	MPEC reformulated through KKT (MILP)

Pediaditis *et al.* [80]	Tariff design	Demand response actions by prosumers	KKT/MIQP
Hoarau *et al.* [81]	Tariff design	Electricity costs of consumers	Not found
Li *et al.* [83]	Siting of DGs and ESSs	Operation of ESSs	IM/Binary PSO
Sharma *et al.* [84]	Sizing of BESS in the presence of DG systems	Operation of ESSs	GA
Sheikhahmadi *et al.* [85]	Operation of DISCO	Day-ahead market clearing	KKT/MILP
Joo *et al.* [86]	Local home energy management system	Global home energy management system	MILP
Gao *et al.* [87]	Integrated planning of DG and electrical grid	Benefits of DG	IM/Binary PSO
Babacan *et al.* [88]	Siting and sizing of ESSs in the presence of DG systems	Operation of ESSs	IM/GA/LP
Bahramara *et al.* [89]	DISCO profit	Cost of microgrids	KKT/MILP
Liu *et al.* [82]	Transmission grid planning	Distribution grid planning	IM/mixed-integer SOCP model/ mixed-integer semidefinite Programming
Li *et al.* [90]	Distribution grid planning	Distribution grid operation	IM
Misaghi *et al.* [91]	DG investor’s profit	Market clearing and upgrade in the substation	KKT/MILP
Marquez *et al.* [92]	Siting and sizing of DG	DG and distribution grid operation	MILP
Model proposed in Chapter 6	Tariff and compensation design and DG investments	Operational aspects (grid modeling)	IM/MINLP/LP

3 THE CONVENTIONAL TAROT MODEL

This chapter presents the conventional TAROT model, *i.e.*, the model formerly proposed by Arango *et al.* [16], which does not explicitly include DERs.

The TAROT model aims to represent the regulated electricity market by quantifying economic flows between agents. Figure 3.1 depicts the model diagram. The green circles represent the market players' surpluses. In turn, the red circles are the costs inherent to the electricity distribution activity in a regulated market. In summary, the consumer surplus (economic consumer added - ECA) is given by the energy economic utility, *i.e.*, the quality of life added by electricity consumption, subtracted from the revenue or electricity bill paid to the DISCO, as pointed out by the arrows in Figure 3.1. On the other hand, the DISCO surplus (economic value added - EVA) is given by the revenue subtracted from all costs depicted in red. DERs are assumed to influence the operational costs and energy loss costs, as further discussed. Finally, socioeconomic welfare (economic wealth added - EWA) is defined as the overall benefit of society arising from the economic transaction, *i.e.*, the sum of ECA and EVA. In the following sections, each term represented in Figure 3.1 is detailed.

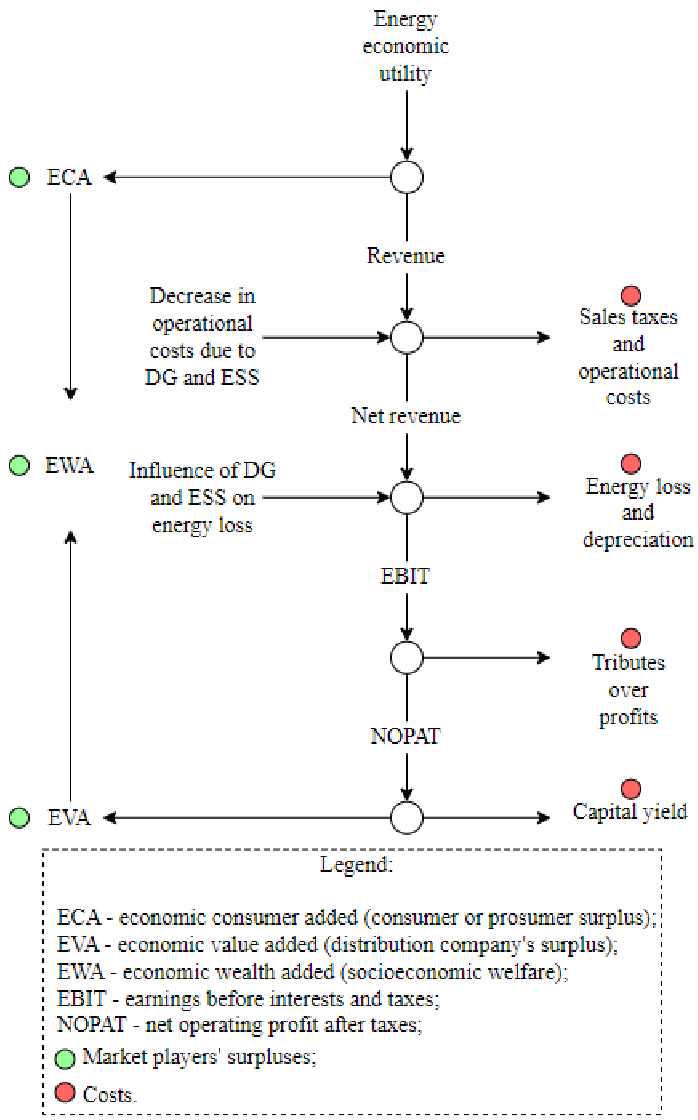

Figure 3.1. Block diagram of economic flows in a regulated electricity market.

3.1 Consumer model

The energy economic utility, which measures the quality of life added by electricity consumption, is given by Equation (3.1):

$$U = aE - \frac{b}{2}E^2 \tag{3.1}$$

where: U is the energy economic utility. a and b are parameters associated with the willingness to consume electricity and the degree of satisfaction with the consumed electricity, respectively. E is the electricity consumption. The social aspect of the TAROT is introduced through the energy economic utility, given that it is related to the consumers' quality of life.

The revenue or electricity bill paid to the DISCO is given by Equation (3.2):

$$R = TE \tag{3.2}$$

where: R is the revenue and T is the regulated electricity tariff.

ECA is modeled by Equation (3.3):

$$ECA = aE - \frac{b}{2}E^2 - R \tag{3.3}$$

Consumers naturally seek to adjust electricity consumption to maximize their surplus, which is done by equaling the marginal utility to the marginal revenue, as equated in (3.4):

$$T = a - bE \tag{3.4}$$

Equation (3.4) quantifies electricity consumption variations due to tariff variations, *i.e.*, demand response (DR) issues.

3.2 Regulated DISCO model

The regulated DISCO's costs related to operational expenses, energy loss, and grid depreciation are modeled by Equation (3.5):

$$C_1 = eE + p\frac{E^2}{B} + dB \tag{3.5}$$

where: C_1 is the above mentioned costs. e, p, and d are parameters associated with the operational costs, energy loss costs, and grid depreciation, respectively. B is the grid investment.

The tributes over sales are proportional to the revenue, as equated in (3.6):

$$TRIB_S = \mu R \tag{3.6}$$

where: $TRIB_S$ is the tributes over sales and μ is the sales taxes parameter.

In turn, the tributes over profits are given by Equation (3.7):

$$TRIB_P = t_t(R - C_1 - \mu R) \tag{3.7}$$

where: $TRIB_P$ is the tributes over profits and t_t is the tax fee.

The capital yield is modeled by Equation (3.8):

$$Y = r_W B \tag{3.8}$$

where: Y is the capital yield and r_W is the weighted average cost of capital (WACC).

The overall cost is given by the sum of Equations (3.5), (3.6), (3.7), and (3.8), as equated in (3.9):

$$C = eE + p\frac{E^2}{B} + dB + \mu R + t_t(R - C_1 - \mu R) + r_W B \tag{3.9}$$

where: C is the overall cost.

EVA is given by Equation (3.10):

$$EVA = R - C \tag{3.10}$$

After some simplifications, Equation (3.11) is obtained:

$$EVA = (1 - t_t)\left[R - \left(eE + p\frac{E^2}{B} + \mu R + Bk\right)\right] \tag{3.11}$$

where: k is the hurdle rate for aggregation of value to the DISCO, which is given by Equation (3.12):

$$k = d + \frac{r_w}{1 - t_t} \tag{3.12}$$

The optimal grid investment, *i.e.*, the investment that the DISCO should consider to maximize its surplus, is obtained by Equation (3.13):

$$B^* = \sqrt{\frac{p}{k}}E \tag{3.13}$$

If optimal grid investments are carried out, the DISCO surplus is given by Equation (3.14):

$$EVA = (1 - t_t)\left[R - \left(eE + 2\sqrt{pk}E + \mu R\right)\right] \tag{3.14}$$

3.3 Overall socioeconomic model

EWA is given by Equation (3.15):

$$EWA = aE - \frac{b}{2}E^2 - R + (1 - t_t)\left[R - \left(eE + p\frac{E^2}{B} + \mu R + Bk\right)\right] \tag{3.15}$$

The regulatory agency seeks to maximize EWA. However, it is essential to maintain market sustainability, *i.e.*, avoid $EVA < 0$ and, consequently, company bankruptcy. In Brazil, ANEEL adopts Equation (3.16) to maximize EWA with guaranteed market sustainability:

$$EVA = 0 \tag{3.16}$$

Equation (3.16) guarantees a state of financial economic equilibrium (FEE) for the DISCO since all its costs can be paid. At the same time, maximum electricity affordability for consumers is ensured.

3.4 Application of the TAROT model in the context of the COVID-19 pandemic

In this section, the TAROT model is applied to 39 Brazilian concession areas to analyze the potential impacts of the COVID-19 pandemic on the regulated electricity market. Among these 39 concession areas, 20 had access to a public policy implemented by ANEEL called COVID-account [4]. Such public policy authorized bank loans by DISCOs to cover deficits or anticipate revenues. ANEEL established a total loan limit of 16.1 GR$ to be paid in 60 months, with an interest rate of 2.8% *p.a.*. The agency's justification was that significant short-term tariff raises would be required if no measures were implemented. Given the COVID-account implementation, the analysis is separated into two groups: the COVID-account group (CAG) and the non-COVID-account group (NCAG). The results for the CAG include the loan. Further details can be found in Paper *a*.

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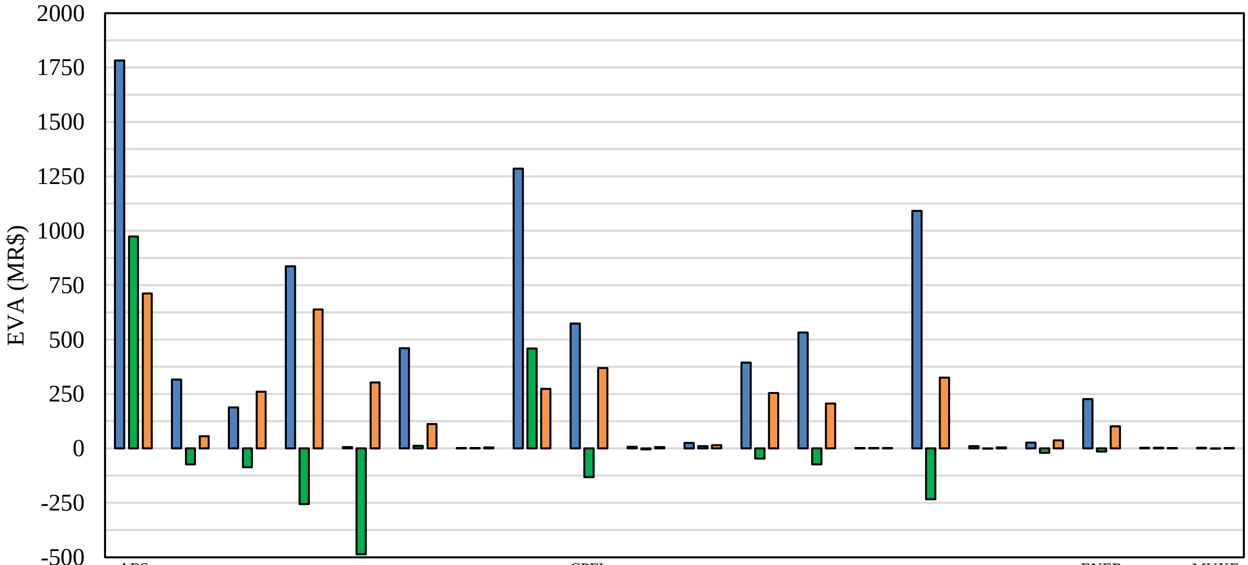
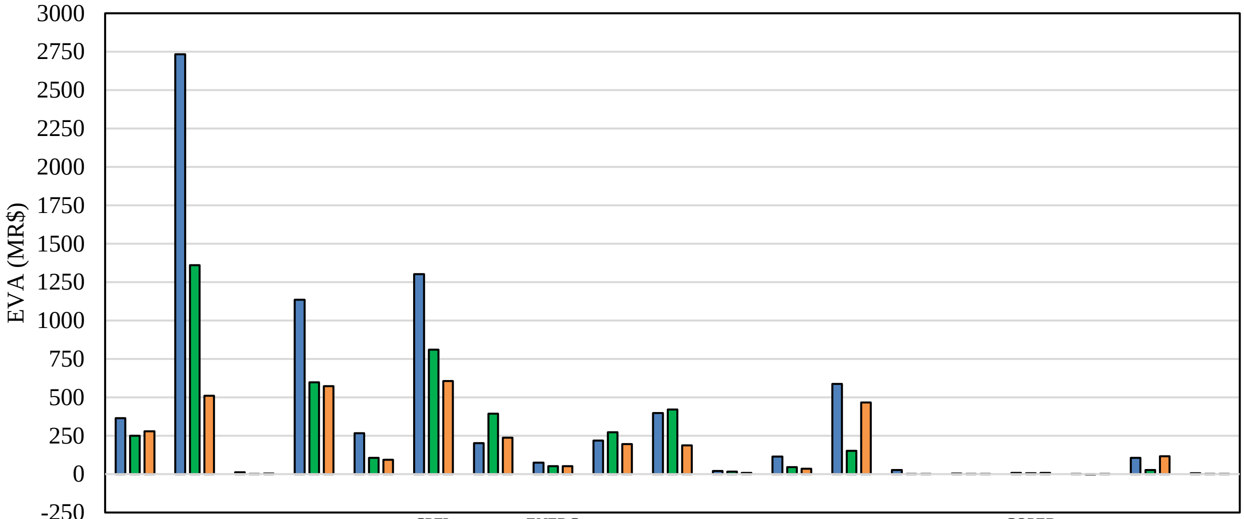
[4] This study was conducted in late 2020. At the time, only 20 concession areas had access to the COVID-account.

The surpluses of the DISCOs for the CAG and NCAG are illustrated in Figures 3.2 and 3.3, respectively. The period from 2018 to 2019 is used for comparison purposes since the pandemic had not yet occurred at the time. For the CAG, the year 2020 was worse than 2019 for 4 of the 20 DISCOs, and their EVA increased by 183 MR$ on average. On the other hand, for the NCAG, the year 2020 was worse for 11 of the 19 DISCOs, and their EVA decreased by 60 MR$ on average. Therefore, the results suggest that the COVID-19 pandemic might have harmed the DISCOs significantly, assuming the absence of public policies.



	AES Eletropaulo	CEB-DIS	CEEE-D	CELESC-DIS	CELG-D	CEMAR	CHESP	COPEL-DIS	CPFL PIRATININGA	DEMEI	DMED	EDP ES	EDP SP	EFLUL	ELEKTRO	ELETROCAR	ELFSM	ENERGISA PB	HIDROPAN	MUXENERGIA
2018	1783	317	189	837	6	461	2	1286	575	8	26	395	533	3	1092	11	28	227	4	3
2019	973	-73	-87	-255	-486	13	1	459	-132	-3	11	-47	-73	0	-233	-1	-21	-14	3	-1
2020	712	56	261	638	304	112	4	274	370	6	16	254	207	0	326	4	37	102	2	2

Figure 3.2. DISCO surplus of the CAG.



	CELPE	CEMIG -D	COCEL	COELB A	COSER N	CPFL PAULI STA	ENEL CE	ENERG ISA MG	ENERG ISA MS	ENERG ISA MT	ENERG ISA NF	ENERG ISA SE	RGE SUL	SULGI PE	UHENP AL	COPER ALIAN ÇA	EFLJC	ENERG ISA TO	FORCE L
2018	365	2733	12	1135	266	1302	201	74	219	397	20	113	587	28	4	8	1	106	5
2019	250	1360	0	597	106	809	393	51	274	421	16	45	151	2	2	6	0	26	1
2020	279	510	4	573	93	606	237	52	195	187	8	35	467	2	1	8	0	117	1

Figure 3.3. DISCO surplus of the NCAG.

It is essential to assess the characteristics of the most affected DISCOs. Table 3.1 describes the EVA and return on investment (ROI) variations from 2019 to 2020, the regions of the concession areas, the number of consumer units, and the commercial consumption share. Spearman's correlation coefficient can be used to verify correlations between the variables [5]. It is calculated by Equation (3.17):

$$\rho = 1 - \frac{6\sum {d_i}^2}{n^3 - n} \tag{3.17}$$

where: d_i is the difference between the two ranks of each observation, and n is the number of observations.

By applying Equation (3.17), one obtains Spearman's coefficients of 0.40 and –0.30 between the EVA variation and the number of consumer units for the CAG and NCAG, respectively. Therefore, for the CAG, the bigger the DISCO, the greater the upward trend of EVA, whereas for the NCAG, the bigger the DISCO, the greater the downward trend of EVA. However, weak correlations are verified, *i.e.*, there is a considerable number of outliers. Other factors, such as the region of the concession areas and the shares of residential, commercial, and industrial consumption, are likely to influence the EVA variation and reduce the strength of the calculated correlations.

In turn, a Spearman's coefficient of –0.44 was obtained between the commercial consumption share and the ROI variation for the NCAG. The ROI is suitable for this analysis since it decreases the influence

[5] Spearman's correlation coefficient is effectively applicable when a non-linear relationship is verified (the TAROT is a non-linear model), as it addresses monotonic relationships instead of linear relationships.

that the number of consumer units has on the performance of the companies. The commercial sector suffered the greatest demand reduction due to the pandemic. Thus, a negative correlation was to be expected. However, a significant number of outliers is also verified.

TABLE 3.1. RANKING OF THE MOST AFFECTED CONCESSION AREAS.

DISCO	COVID-account?	EVA variation from 2019 to 2020 (MR$)	Region	Number of consumer units (thousands)	Commercial consumption share (%)	ROI variation from 2019 to 2020 (%)
CELESC-DIS	Yes	893.49	South	3087	14.9	1.10
CELG-D	Yes	790.21	Midwest	3096	16.3	0.00
ELEKTRO	Yes	558.99	Southeast	2734	13.2	0.80
CPFL PIRATININGA	Yes	501.76	Southeast	1770	13.8	-1.90
CEEE-D	Yes	347.57	South	1762	20.9	-0.90
EDP ES	Yes	301.33	Southeast	1592	13.6	0.60
EDP SP	Yes	279.58	Southeast	1967	13.6	-2.30
CEB-DIS	Yes	128.32	Midwest	1085	28.0	-0.30
ENERGISA PB	Yes	116.26	Northeast	1455	17.8	0.00
CEMAR	Yes	99.48	Northeast	2561	16.9	-0.30
ELFSM	Yes	57.96	Midwest	116	21.7	3.40
DEMEI	Yes	9.24	Southeast	34	27.4	2.90
ELETROCAR	Yes	5.22	South	38	20.8	1.70
DMED	Yes	4.89	South	79	12.9	-2.70
CHESP	Yes	3.13	Southeast	38	23.0	0.40
MUXENERGIA	Yes	2.76	South	12	14.1	4.00
EFLUL	Yes	-0.14	South	7	5.5	-0.10
HIDROPAN	Yes	-1.87	South	19	12.7	-0.10
COPEL-DIS	Yes	-184.76	South	4749	21.5	0.50
AES Eletropaulo	Yes	-261.59	Southeast	7010	27.3	0.70
RGE SUL	No	315.83	South	2880	14.2	3.74
ENERGISA TO	No	90.80	North	604	19.1	-4.27
CELPE	No	28.51	Northeast	3750	22.2	0.27
COCEL	No	3.50	South	52	13.3	2.11
COPERALIANÇA	No	1.73	South	74	14.5	1.18
EFLJC	No	0.23	South	4	17.8	-9.83
SULGIPE	No	0.16	Northeast	151	11.8	0.00
ENERGISA MG	No	0.11	Southeast	462	18.5	0.36
FORCEL	No	-0.08	South	8	10.3	1.52
UHENPAL	No	-0.99	South	16	20.0	0.51
ENERGISA NF	No	-8.08	Southeast	109	19.6	-0.23
ENERGISA SE	No	-9.94	Northeast	790	22.3	-0.21
COSERN	No	-13.09	Northeast	1480	21.7	-0.04
COELBA	No	-24.31	Northeast	6120	20.9	0.14
ENERGISA MS	No	-78.78	Midwest	1050	23.2	0.13
ENEL CE	No	-155.88	Northeast	3780	20.7	0.22
CPFL PAULISTA	No	-203.19	Southeast	4520	16.6	1.45
ENERGISA MT	No	-234.47	Midwest	1	23.9	-0.30
CEMIG-D	No	-850.64	Southeast	8550	12.3	0.07

The EVA variation per region is depicted in Figure 3.4. The Southeast region might have been more affected by the pandemic, given its substantial demand reduction. CEMIG-D, located in Minas Gerais, was the main responsible for the negative impact (approximately 80%). Most DISCOs from São Paulo had access to the COVID-account. Thus, their EVA did not decrease remarkably.

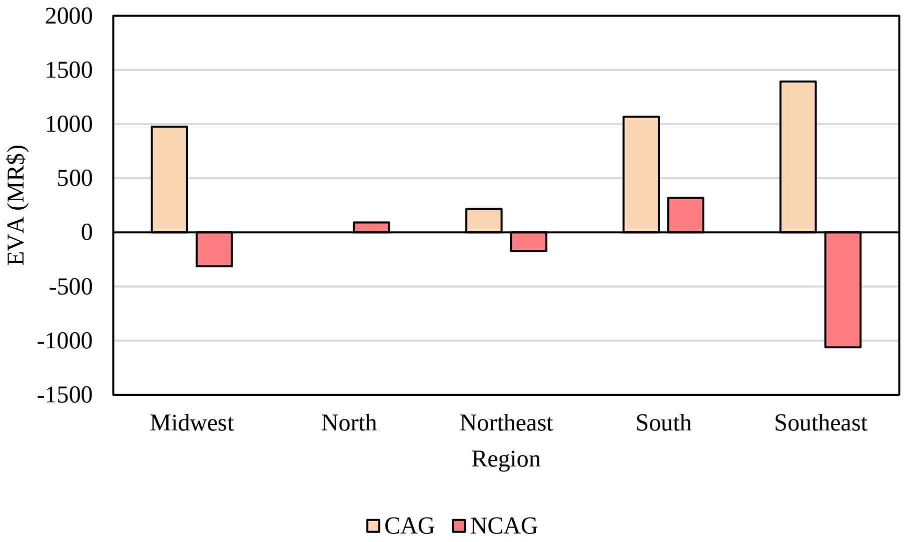


Figure 3.4. EVA variation per region. Reference year: 2020.

Based on Equation (3.16), the influence of the COVID-account on regulated tariffs is illustrated in Figure 3.5. The public policy fulfills its purpose of decreasing tariffs in the short term. However, the long-term consequences of the loan, *i.e.*, its payment in 60 months with an interest rate of 2.8% *p.a.*, are not represented. Evidently, regulated tariffs are expected to increase over time, given the introduced interest rate and their natural growth tendencies that take place even in a pandemic-free context.

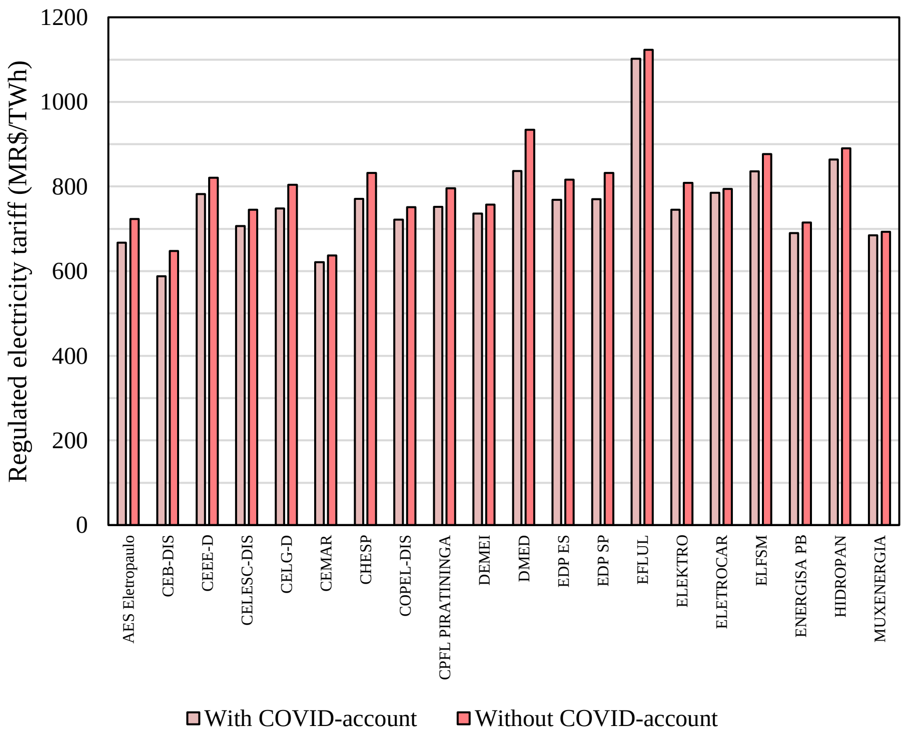


Figure 3.5. Influence of the COVID-account on the tariffs. Reference year: 2020.

Although the COVID-account presented satisfactory short-term tariff reductions, there will be negative long-term consequences. Moreover, consumers have no choice whether they accept the loan terms. Therefore, a relatively simple and interest-free public policy to mitigate the impact of the pandemic is proposed here. The idea is to maintain ECA constant and impose $EVA = 0$ before and after the pandemic. To do so, it is assumed that ANEEL can modify the regulated tariffs (T) and sales taxes parameters (μ). Modifying the sales taxes parameters is analogous to promoting tax exemptions of ICMS, PIS, or COFINS [6].

First, it is analyzed how the regulated tariff can be modified to maintain ECA constant. From Equations (3.2), (3.3), and (3.4), Equation (3.18) is obtained:

$$E = \sqrt{\frac{2ECA}{b}} \tag{3.18}$$

Based on Equations (3.4) and (3.18), the tariff can be represented by Equation (3.19):

$$T = a - \sqrt{2bECA} \tag{3.19}$$

The tariff equated in Equation (3.19) implies a constant ECA. However, it does not result in $EVA = 0$, unless the sales taxes parameter is modified. Based on Equations (3.4) and (3.14), the sales taxes parameter that results in $EVA = 0$ is given by Equation (3.20):

$$a - \mu a - e - 2\sqrt{pk} + (\mu b - b)E = 0 \tag{3.20}$$

Based on Equations (3.18) and (3.20), Equation (3.21) is obtained:

$$\mu = 1 + \frac{e + 2\sqrt{pk}}{\sqrt{2b(ECA)} - a} \tag{3.21}$$

The proposed public policy was applied to the concession areas of CEMIG-D, ENEL CE, ENERGISA NF, and HIDROPAN since they exhibited reductions in both ECA and EVA from 2019 to 2020. The required tariffs (Equation (3.19)) and sales taxes parameters (Equation (3.21)) to implement the public policy are illustrated in Figures 3.6 and 3.7, respectively. Some concession areas do not require significant changes (*e.g.*, HIDROPAN). Hence, minor tariff reductions and tax exemptions would be enough in such cases. Specifically for ENEL CE, tax exemptions are unnecessary due to its positive EVA.

In turn, CEMIG-D requires substantial changes. The impact of the proposed public policy on the collection of ICMS is around 5.5% [7]. Thus, completely mitigating the impact of the pandemic on the market might not be a feasible approach. However, it is also possible to propose partial mitigations based on the TAROT model, which are more easily implementable solutions.

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[6] ICMS, PIS, and COFINS are Brazilian taxes associated with the consumption of goods and services, social integration program, and contribution to social security financing.

[7] ICMS is the main tax that composes the μ parameter.

Although results suggest that the pandemic might have impacted the market substantially, natural market changes can occur over time. Thus, it is challenging to infer the real impact of the pandemic.

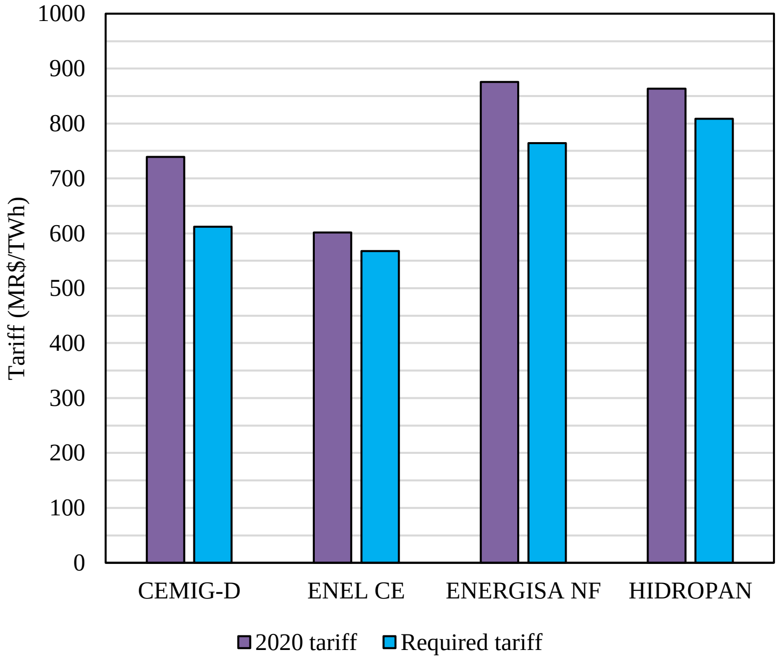

Figure 3.6. Required tariffs to implement the proposed public policy.

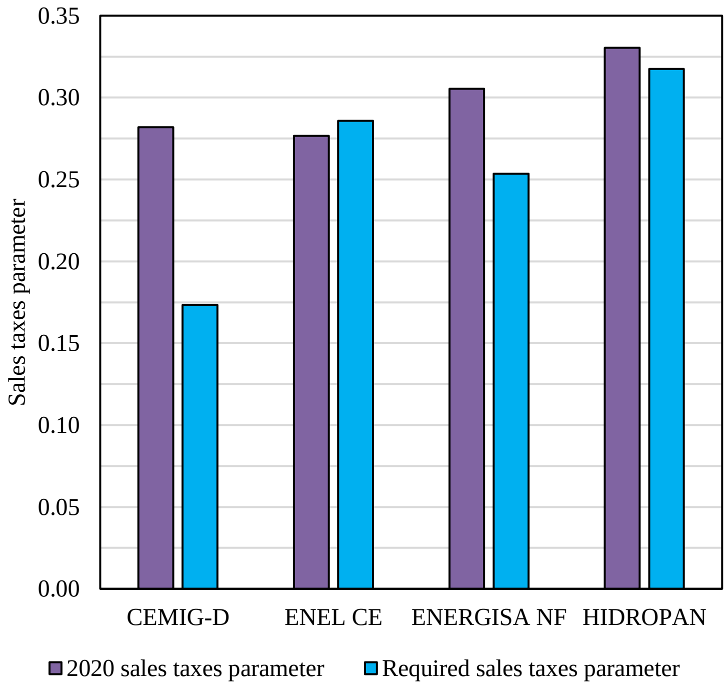

Figure 3.7. Required sales taxes parameter to implement the proposed public policy.

This chapter achieved objective (*i*) and answered RQ1.

4 THE TAROT MODEL IN THE CONTEXT OF DERS INTEGRATION

This chapter presents an extension of the TAROT model that explicitly includes DERs (DG and ESSs) and TOU rates and shows how the BDM can be combined with the TAROT to enable time-series analyses of the regulated electricity market in the context of DERs integration. Similar models have been applied in Papers *c*, *d*, *e*.

4.1 Consumer and prosumer model

In the TOU rates context, the utility function is modeled by Equation (4.1):

$$U = a_O E_O + a_I E_I + a_P E_P - \frac{1}{2}\left(b_O {E_O}^2 + b_I {E_I}^2 + b_P {E_P}^2\right) \tag{4.1}$$

where: the indexes O, I, and P concern the off-peak, intermediate, and peak periods, respectively. a and b are parameters associated with the willingness to consume electricity and the degree of satisfaction with the consumed electricity, respectively. E is the electricity consumption. For simplicity, the effects of cross-elasticities are disregarded in Equation (4.1). Information on how cross-elasticities can influence the utility function is available in Costa *et al.* [93].

In some cases, it is beneficial to express electricity consumption in terms of ratios, as equated in (4.2):

$$\begin{cases} E_O = P_O E \\ E_I = P_I E \\ E_P = P_P E \end{cases} \tag{4.2}$$

where: P is the electricity consumption ratio.

For simplicity, Equation (4.3) is also assumed:

$$E = E_O + E_I + E_P \tag{4.3}$$

where: E is the overall electricity consumption.

The revenue or electricity bill paid to the DISCO is given by Equation (4.4):

$$\begin{gathered} R = T_O E_O + T_I E_I + T_P E_P \\ -\{T_O \lambda_O [l_O + (1 - l_O)n] + T_I \lambda_I [l_I + (1 - l_I)n] + T_P \lambda_P [l_P + (1 - l_P)n]\} E_G \end{gathered} \tag{4.4}$$

where: T is the regulated electricity tariff. n is the compensation policy parameter for the electricity injected into the grid. For the net metering policy, $n = 1$, whereas for distinct policies (*e.g.*, OL analyzed in Chapter 5), $n \neq 1$. E_G is the generated electricity from DG. λ is the ratio of generated electricity from DG used in each period. l is the self-consumption ratio, which is assumed to be independent of the compensation policy, *i.e.*, only the electricity injected into the grid $(1 - l)$ is assumed to be dependent on the compensation policy.

The DG systems' capital expenditures (CAPEX) and operational expenditures (OPEX) are modeled by Equation (4.5):

$$C_D = sE_G \tag{4.5}$$

where: C_D is the CAPEX and OPEX and s is a cost parameter related to the LCOE. For simplicity, a linear equation is assumed, and economies of scale are embedded in s.

The consumer or prosumer surplus is given by Equation (4.6):

$$ECA = a_O E_O + a_I E_I + a_P E_P - \frac{1}{2}\left(b_O {E_O}^2 + b_I {E_I}^2 + b_P {E_P}^2\right) - R - sE_G \tag{4.6}$$

DR issues, *i.e.*, the relationships between tariffs and consumption, are modeled in a simplified manner, as equated in (4.7):

$$\begin{gathered} T_O = a_O - b_O E_O \\ T_I = a_I - b_I E_I \\ T_P = a_P - b_P E_P \end{gathered} \tag{4.7}$$

4.2 Regulated DISCO model and socioeconomic welfare

Although the TAROT usually does not model the grid in detail, it is necessary to adapt the energy loss cost term pE^2/B equated in (3.5) to the context of DERs integration. Previous research on the topic has demonstrated that the relationship between energy loss and DG penetration is given by a U-shape trajectory, *i.e.*, a parabola concave upwards [94], [95], [96], [97], [98]. Specifically, DG tends to be beneficial for low penetrations since it reduces conventional system usage that requires extensive electricity transport. On the other hand, DG tends to increase energy loss for high penetrations due to reverse power flow. Therefore, energy loss is modeled based on a U-shape trajectory. Moreover, DISCOs purchase electricity in the wholesale market under long-term contracts to supply captive consumers in Brazil. Hence, price volatility is limited, and it is reasonable to assume that the energy loss cost is proportional to energy loss. Consequently, the energy loss cost term is modeled by Equation (4.8):

$$H = \frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{B} \tag{4.8}$$

where: H is the energy loss cost. pE^2/B is the conventional energy loss cost term. E_G/E is the DG penetration. f and g are adjustable parameters defined based on power flow simulations. Power flow simulations were conducted on Paper *c* for varying penetrations of DG and ESSs. Given that data on the actual grid topologies and electrical parameters of the Brazilian distribution systems were not found, Paper *c* assumed a relatively simple test grid (21 buses) with characteristics of real distribution systems. The results obtained were used for defining f and g. In particular, after conducting power flow simulations for varying DERs penetration, a regression technique was applied, resulting in the parabola represented in Equation (4.9):

$$E_L = f_1 \left(\frac{E_G}{E}\right)^2 + g_1 \frac{E_G}{E} + h_1 \tag{4.9}$$

where: E_L is the energy loss percentage. f_1, g_1, and h_1 are the parameters obtained from the regression.

Finally, Equations (4.10) and (4.11) are used to convert the energy loss parameters into monetary terms (MR$²):

$$g = pE^2 \frac{g_1}{h_1} \tag{4.10}$$

$$f = pE^2 \frac{f_1}{h_1} \tag{4.11}$$

Equation (4.8) is an approximation since energy loss depends on several factors, such as the location of the DG systems and the source. However, it fulfills the model's purpose of providing a satisfactory market overview with limited complexity. More accurate energy loss modeling is done in Chapter 6 through bi-level programming.

DERs also modify (decrease) the operational costs, as per Equation (4.12):

$$Q = eE - e'E_G \tag{4.12}$$

where: Q is the operational costs. eE is the conventional operational costs term and $e'E_G$ models the decrease in operational costs due to DERs. To properly quantify the parameter e', one should evaluate which categories of operational costs are significantly influenced by DERs. Operational costs include: (*i*) sector charges defined in specific regulation (mainly subsidies related to public policies), (*ii*) transmission costs, (*iii*) energy purchase costs, (*iv*) administration, operation & maintenance (O&M) costs, (*v*) costs related to mobile and real estate infrastructures (*e.g.*, offices), and (*vi*) revenues from secondary activities[8] (*e.g.*, telecom infrastructure sharing). Among these terms, DERs significantly influence the transmission costs and energy purchase costs since transmission is mostly unnecessary for electricity supplied from DG systems, and DG decreases the amount of electricity purchased by the DISCO. DERs might also influence O&M costs, however, it is not clear how this occurs since DG may be linked to the increased complexity of procedures and maintenance [99]. Hence, the influence of DERs on O&M costs is disregarded. Consequently, the parameters e and e' are modeled by Equations (4.13) and (4.14):

$$e = \frac{E_S + C_T + C_C + C_A + C_I - O_R}{E} \tag{4.13}$$

$$e' = \frac{C_T + C_C}{E} \tag{4.14}$$

[8] Revenues from secondary activities have a negative sign in Equation (4.10) since they are associated with benefits, not costs.

where: E_S, C_T, C_C, C_A, C_I, and O_R are the sector charges, transmissions costs, energy purchase costs, O&M costs, costs related to mobile and real estate infrastructures, and revenues from secondary activities, respectively. Equation (4.13) is a conventional equation applied to obtain the parameter e in the TAROT model.

Apart from the energy loss and operational costs, the DISCO's cost structure is assumed to be similar to that of Chapter 3. Hence, the DISCO surplus is modeled by Equation (4.15):

$$EVA = (1 - t_t)\left\{R - \left[eE - e'E_G + \frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{B} + \mu R + Bk\right]\right\} \tag{4.15}$$

The proposed energy loss cost structure implies a distinct optimal grid investment, as equated in (4.16):

$$B^* = \sqrt{\frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{k}} \tag{4.16}$$

where: B^* is the optimal grid investment.

The socioeconomic welfare is again modeled by the sum of ECA and EVA, as equated in (4.17):

$$\begin{aligned} EWA = {} & a_O E_O + a_I E_I + a_P E_P - \frac{1}{2}\left(b_O {E_O}^2 + b_I {E_I}^2 + b_P {E_P}^2\right) - R - sE_G \\ & + (1 - t_t)\left\{R - \left[eE - e'E_G + \frac{f\left(\frac{E_G}{E}\right)^2 + g\frac{E_G}{E} + pE^2}{B} + \mu R + Bk\right]\right\} \end{aligned} \tag{4.17}$$

Equation (3.16) can still be used to ensure maximum electricity affordability for consumers and FEE for the DISCO. Moreover, the proposed model enables the regulatory agency to promote energy shifting by following two simple steps: (*i*) setting the ratios P_O, P_I, and P_P as intended in Equation (4.2) and (*ii*) applying Equations (3.16) and (4.7). However, it is noteworthy that the intended energy shifting only occurs if the demand elasticities are correctly estimated since they influence the parameters a_O, a_I, and a_P. Furthermore, even if the demand elasticities are correctly estimated, it is usually not possible to promote substantial energy shifting due to the inelastic characteristic of electricity, *i.e.*, large tariff modifications imply little change in consumption.

4.3 Case study: time-independent TAROT with DER

In this section, a case study is conducted to verify the behavior of the proposed TAROT model. The BDM is not assumed yet, *i.e.*, the analysis is time-independent. PV DG systems are considered since they account for more than 99% of distributed connections [9] [100]. A fixed storage capacity of 35% is assumed

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[9] PV DG systems are analyzed in all case studies carried out in this thesis. For simplicity, this information is omitted in the following sections.

for simplicity's sake, as the effects of different storage capacities are further analyzed in Section 4.5. Furthermore, ELEKTRO's concession area located in São Paulo is addressed, focusing on three outcomes: (i) the consequences of increasing DERs penetration, assuming the net metering policy ($n = 1$) and the absence of energy shifting incentives (constant P_O, P_I, and P_P), (ii) the consequences of changes in compensation for the electricity injected into the grid, assuming constant tariffs and the absence of energy shifting incentives, and (iii) the consequences of promoting energy shifting away from the intermediate and peak periods, assuming the net metering policy and a constant DERs penetration ($E_G/E = 8\%$). Further details concerning this case study are available in Paper c, including the performed power flow simulations for estimating the energy loss costs parameters f and g.

4.3.1 Consequences of increasing DERs penetration

The consequences of increasing DERs penetration on the DISCO's revenue, costs, and surplus are presented in Figure 4.1. DERs decrease all categories of costs (operational costs, energy loss and grid-related costs, tributes over sales, and tributes over profits). However, the DISCO's revenue also decreases, given the reduction in electricity sales. The decrease in revenue is more influential than the decrease in costs. Thus, DERs are harmful to the DISCO. That being said, the analyzed DISCO presents a positive EVA for $E_G/E < 18\%$, which is a substantial DERs penetration, especially in the Brazilian context.

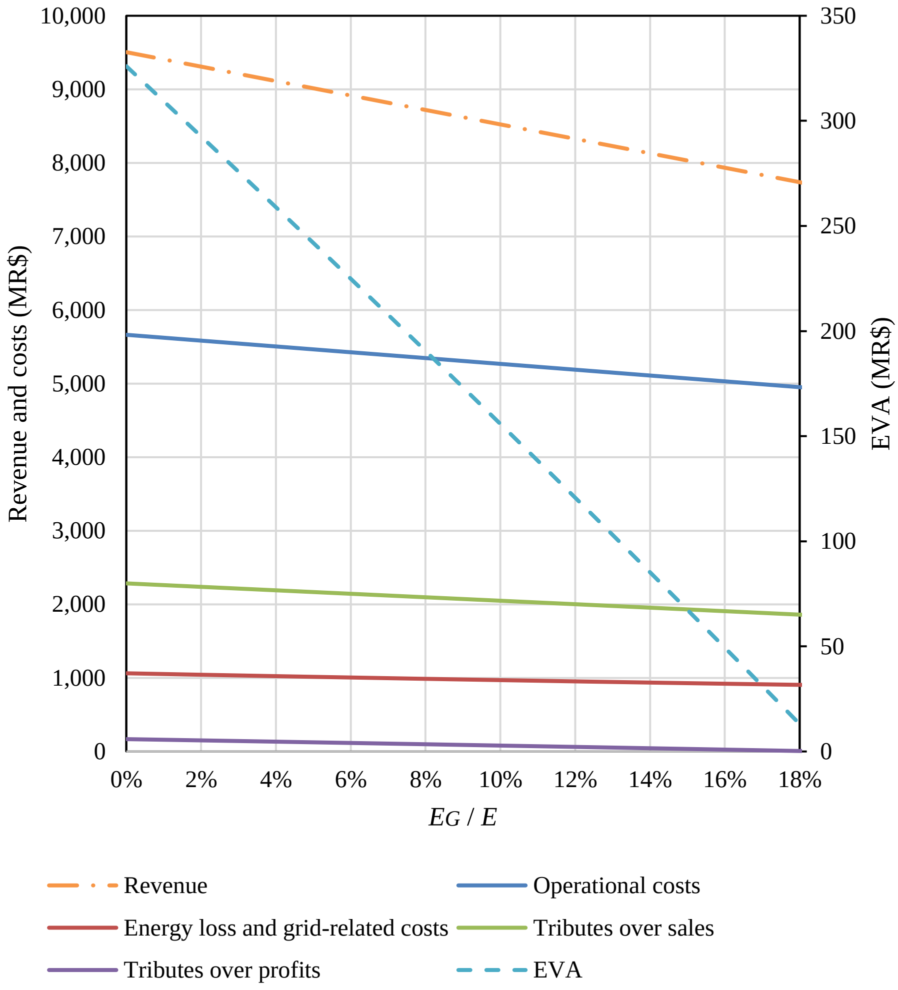

Figure 4.1. Consequences of increasing DERs penetration on the DISCO's revenue, costs, and surplus.

The consequences of increasing DERs penetration on the optimal tariffs, *i.e.*, tariffs that imply $EVA = 0$, are presented in Figure 4.2. The optimal tariffs are lower than the current tariffs for reasonable penetrations ($E_G/E < 18\%$), indicating that current tariffs are excessive. In turn, for higher penetrations, tariff raises are required to ensure FEE for the DISCO. Moreover, the exponential-shaped curves demonstrate that the death spiral process occurs if the penetration increases indiscriminately. Such a process is detailed in Figure 4.3. Additionally, it should be noted that the optimal tariffs increase in fixed proportions due to the absence of energy shifting incentives.

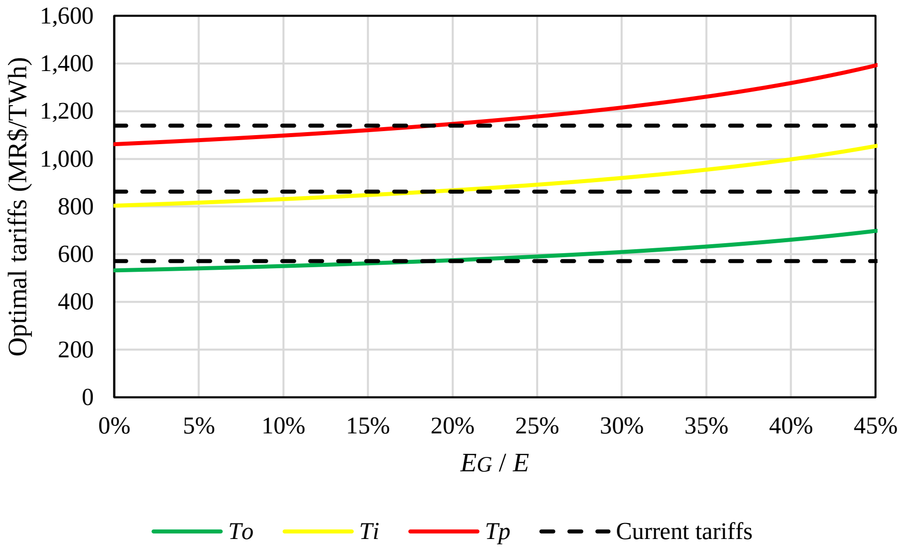

Figure 4.2. Consequences of increasing DERs penetration on the optimal tariffs.

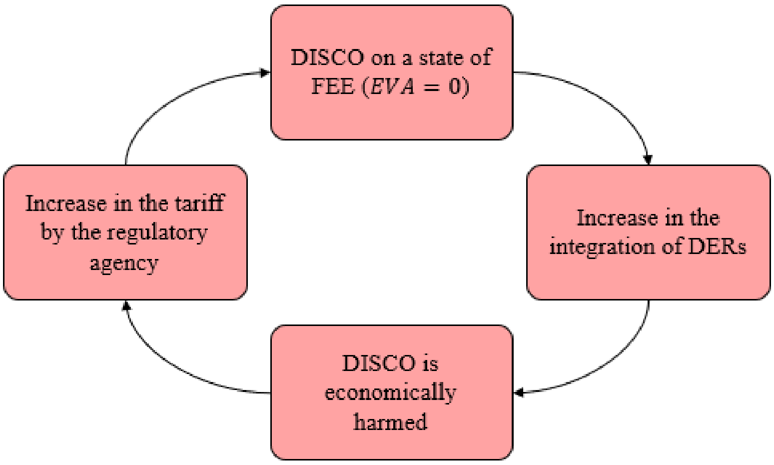

Figure 4.3. Death spiral process.

4.3.2 Consequences of changes in compensation

Section 4.3.1 discussed how the tariffs could be modified to ensure FEE for the DISCO. However, there is an alternative solution to ensure FEE without modifying the tariffs, which consists of controlling the compensation policy parameter for the electricity injected into the grid (n). Specifically, it was demonstrated that DERs are harmful to the DISCO for the net metering policy $n = 1$, but this might not be the case for lower compensations.

By assuming constant tariffs, Figure 4.4 illustrates how the compensation policy parameter can be controlled to ensure FEE. The compensation should be around 70% [10]. The decreasing behavior takes place since, as penetration increases, DERs become less efficient in reducing energy losses.

From the DISCO's perspective, the solutions presented in Section 4.3.1 (variable tariffs) and in this section (variable compensation policy) are similar. However, the latter is seen as a fairer solution from the perspective of conventional consumers who are unable (or do not wish) to invest in DG systems since the compensation policy only affects prosumers. There is also the possibility of simultaneously varying the tariffs and compensation policy parameter. This strategy is more advanced and will be discussed in Chapters 5 and 6.

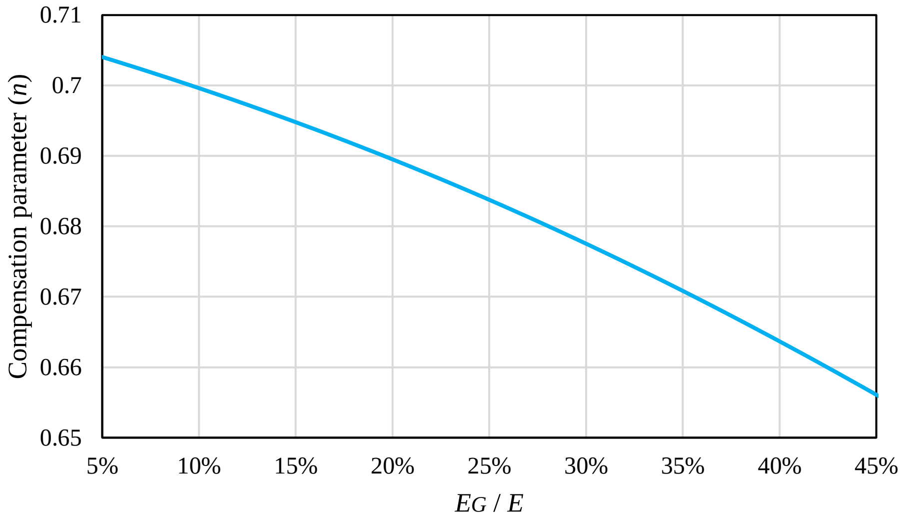

Figure 4.4. Compensation parameter to maintain FEE for the DISCO with constant tariffs.

4.3.3 Consequences of energy shifting incentives

The proposed model can be used to promote energy shifting if the regulatory agency intends to do so. Initially, the consumptions ratios are $P_O = 63\%$, $P_I = 13\%$, and $P_P = 24\%$. Hypothetically, it is assumed that the regulatory agency intends to promote energy shifting away from the intermediate and peak periods as follows: $P_O = 63.75\%$, $P_I = 12.75\%$, and $P_P = 23.5\%$. The small variations are due to the inelastic characteristic of electricity (the elasticity is estimated as 0.14 for the analyzed concession area [101]).

The required tariff variations to promote energy shifting while maintaining $EVA = 0$ are illustrated in Figure 4.5. Naturally, tariffs decrease to increase consumption (off-peak period) and increase to decrease

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[10] Papers *c*, *d* did not consider the distinction between self-consumed DG electricity (parameter *l*) and electricity injected into the grid. If this factor were considered, the value of the compensation policy parameter would be different. Nevertheless, the discussions concerning the results are still valuable.

consumption (intermediate and peak periods). Furthermore, the tariffs vary linearly, as it was assumed that the demand elasticities are constant around the equilibrium point.

It is important to acknowledge that the results presented in this section are very simplified since: (*i*) there is a lack of reliable data on demand elasticities in the Brazilian context, (*ii*) elasticities might vary depending on the market conditions, and (*iii*) the effects of cross-elasticities were disregarded. In practice, tariff variations in one period might affect consumption in another period [93].

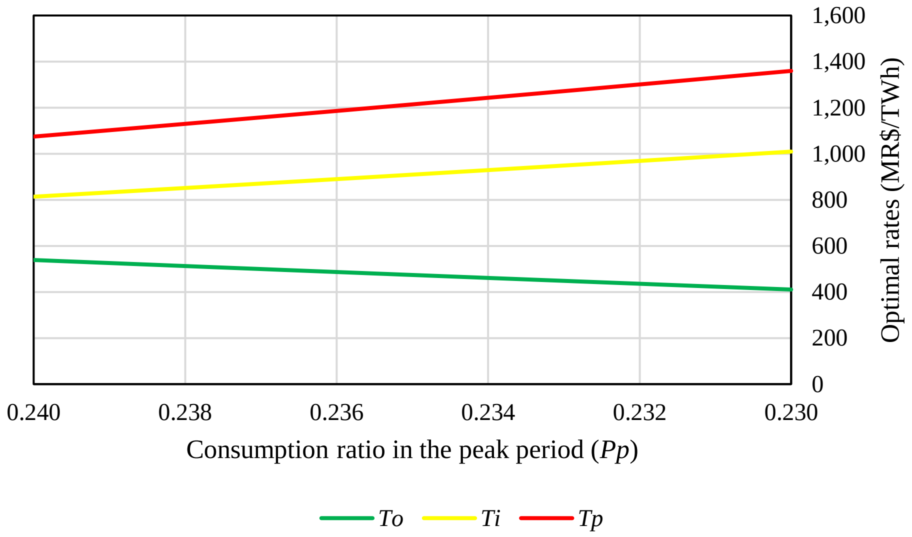

Figure 4.5. Tariff modifications to promote energy shifting while maintaining $EVA = 0$.

4.4 BDM

This section presents the BDM proposed by Beck [23], which is applied deterministically and in an aggregated manner (the most common BDM in the literature). The scenario-based and locational BDM is presented separately in Chapter 6 (a model similar to that proposed by Abud *et al.* [24]), as it is a more advanced model.

The BDM forecasts technology demands (in this case, DERs). Its cumulative distribution function (CDF) is given by Equation (4.18) [25]:

$$F(t) = \frac{1 - e^{-(p_B+q_B)t}}{1 + \frac{q_B}{p_B} e^{-(p_B+q_B)t}} \tag{4.18}$$

where: $F(t)$ is the CDF in time t. p_B and q_B are the innovation and imitation parameters, respectively. Such parameters dictate how fast the curve increases and flattens and should be defined based on historical data (least squares method).

The probability density function (PDF) is given by Equation (4.19):

$$f(t) = \frac{(p_B + q_B)e^{-(p_B+q_B)t}\left\{1 + \frac{q_B}{p_B}\left[1 + e^{-(p_B+q_B)t}\right]\right\}}{\left[1 + \frac{q_B}{p_B}e^{-(p_B+q_B)t}\right]^2} \tag{4.19}$$

where: $f(t)$ is the PDF.

The typical shapes of the CDF and PDF are depicted in Figure 4.6. As verified, the shape of the CDF (purple line) is similar to an S-curve. Specifically, the growth is relatively low at the beginning to model the delay in the demand for new technologies. Those who purchase technology at this stage are called innovators or early adopters. Then, the growth is substantial in the medium term since the technology is already well-regarded by the population. Finally, the curve stagnates in the long term since most of the population that could buy the technology has already bought it, and the technology might become outdated.

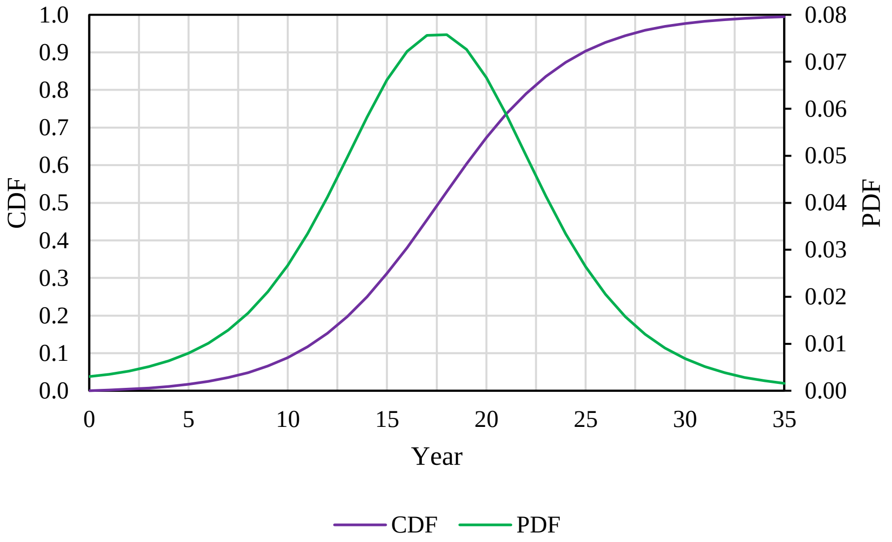

Figure 4.6. Typical BDM's CDF and PDF.

To estimate the generated electricity from DG, Equation (4.20) is used:

$$E_G(t) = E_G(t-1) + m_p m_{mf}(t) f(t) \tag{4.20}$$

where: $E_G(t)$ is the generated electricity from DG. m_p is the market potential. $m_{mf}(t)$ is the maximum market fraction, which is given by Equation (4.21):

$$m_{mf}(t) = e^{-P_{BS}P_{BT}(t)} \tag{4.21}$$

where: P_{BS} is the payback sensitivity and $P_{BT}(t)$ is the payback time. One major advantage of the BDM compared to other forecasting techniques is that it considers the payback time, *i.e.*, it can quantify the impact of regulatory changes (*e.g.*, tariff modifications) on demand for DG systems, which is of utmost importance to fulfill this thesis' purpose.

Given the time-series approach introduced by the BDM, it is beneficial to define a performance index (PEI) for comparing different regulatory solutions, as equated in (4.22):

$$PEI = -EWA(t_0) + \frac{1}{(t_1 - t_0)} \int_{t_0}^{t_1} EWA(t)dt \quad (4.22)$$

where: $EWA(t)$ is the socioeconomic welfare provided by the TAROT model. t_0 and t_1 are the initial and final simulation years, respectively. The PEI corresponds to the mean socioeconomic welfare gain throughout the assessment.

The proposed algorithm for the time-series assessment of the regulated market in the context of DERs integration is illustrated in Figure 4.7. The stopping criterion can be set based on the CDF since it is percentage-based. For instance, Paper d assumed a stopping criterion of $F(t) = 99\%$.

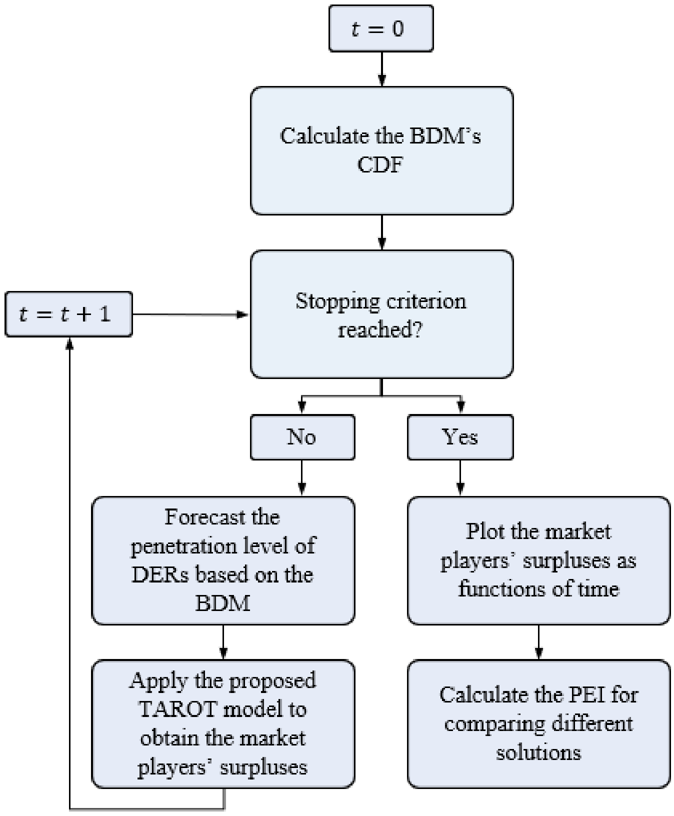

Figure 4.7. Proposed algorithm for the time-series assessment of the regulated market in the context of DERs integration.

4.5 Case study: time-dependent TAROT with DER and BDM

In this section, a time-dependent case study is carried out for CELESC-DIS' concession area located in Santa Catarina. Simulations are performed assuming three scenarios: (1) DG systems without energy storage, (2) DG systems with 50% storage capacity, and (3) DG systems with 100% storage capacity. Prosumers with ESSs are assumed to store electricity from the DG systems in the off-peak period at a tariff T_O to inject it into the grid in the peak period at a higher tariff T_P. Different from Section 4.3, the energy loss costs parameters for systems without storage were estimated based on the IEEE 34 node test feeder with a concentrated location of PV systems based on data from Quezada *et al.* [11] [97]. DG systems with storage are assumed to decrease losses compared to DG systems without storage. This approach was assigned since the main goal is to analyze the qualitative behavior of the model, *i.e.*, the shape of the curves over time. Additionally, the regulated electricity tariff is assumed to be constant so that the analysis reflects the impacts of DERs in the absence of external interventions.

First, simulations are carried out assuming the net metering policy ($n = 1$). Then, it will be demonstrated how the compensation policy parameter can be increased to foster the deployment of ESSs. Further details concerning this case study are available in Paper *d*.

4.5.1 Net metering policy

DG systems with storage present considerably higher payback time due to the additional cost of the batteries. The different payback times among scenarios imply distinct BDM estimations, as shown in Figure 4.8. The estimations for Scenarios (2) and (3) are close since half the compensation of prosumers in Scenario (2) occurs during the off-peak period, which was comparable to the additional cost of batteries in Scenario (3).

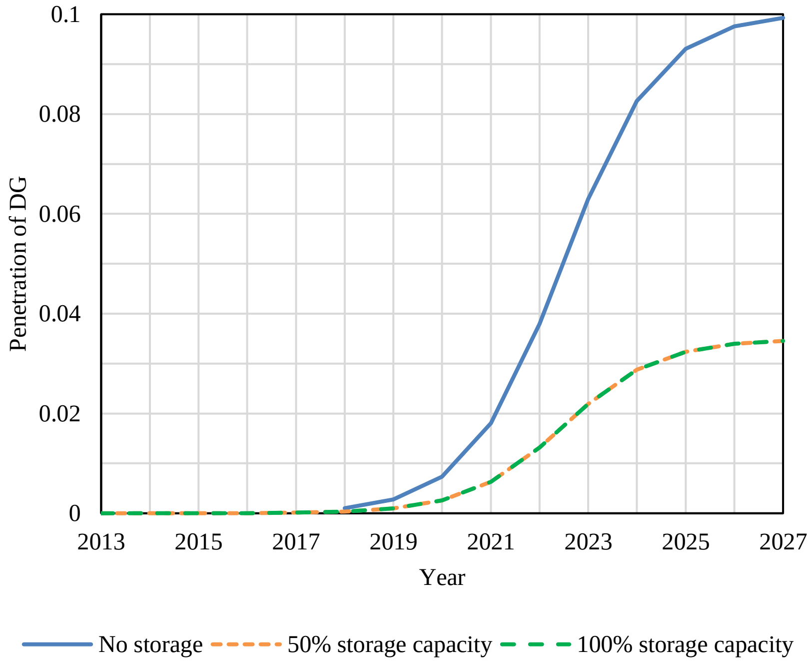

Figure 4.8. BDM estimation.

The energy loss costs over time are presented in Figure 4.9. The faster integration of DG systems without storage causes the energy loss valley, *i.e.*, the low region of the parabola representing a reduction in

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[11] Quezada *et al*. [97] performed power flow simulations to obtain the curve enegy losses × DG penetration. Such a curve was used here.

energy loss, to be exploited earlier. Therefore, DG systems without storage are superior in the short term. However, for such systems, the quadratic parameter f becomes more influential than the proportional parameter g in the long term. Hence, there is a long-term increase in energy loss costs. In turn, the low penetration of systems with storage is not enough to cause an increase in energy loss costs. It is noteworthy that values are highly dependent on grid topology, but qualitative results are expected to reoccur unless ESSs become more economically feasible.

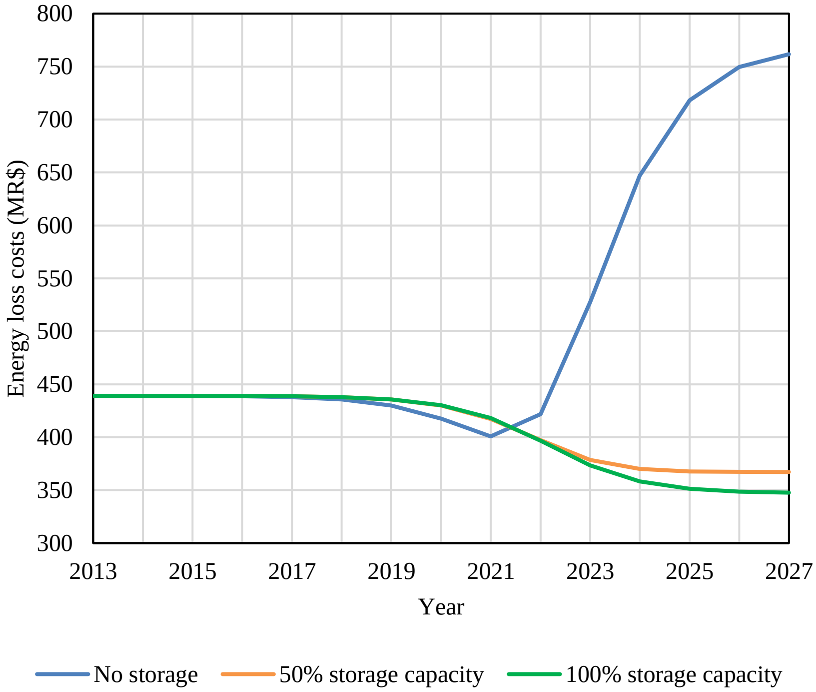

Figure 4.9. Energy loss costs.

The DISCO surplus is presented in Figure 4.10. DG systems with storage have little influence on EVA due to their relatively low penetration and higher efficiency in decreasing energy loss [12]. On the other hand, DG systems without storage are slightly beneficial to the DISCO in the short term due to the low off-peak period tariff and decrease in energy loss costs, but they are significantly detrimental in the long term, as EVA approaches 0 in 2027.

[12] It is emphasized that depending on the off-peak and peak period tariffs, the influence of ESSs on EVA might be higher.

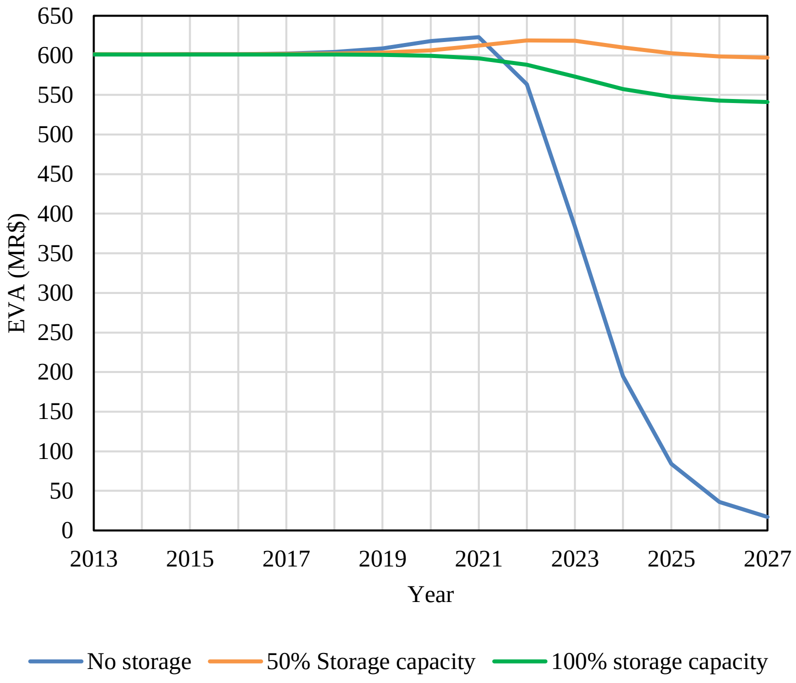

Figure 4.10. DISCO surplus.

The socioeconomic welfare is illustrated in Figure 4.11. DG systems without storage are beneficial in the short term. However, DG systems with storage overcome their counterparts in the long term. The PEI, *i.e.*, the mean socioeconomic welfare gain throughout the simulation period, can be calculated for a quantitative comparison between the scenarios. The PEI for Scenarios (1), (2), and (3) are 129.9 MR$, 110.2 MR$, and 120.5 MR$, respectively. Thus, Scenario (1) is overall superior for the assumed parameters.

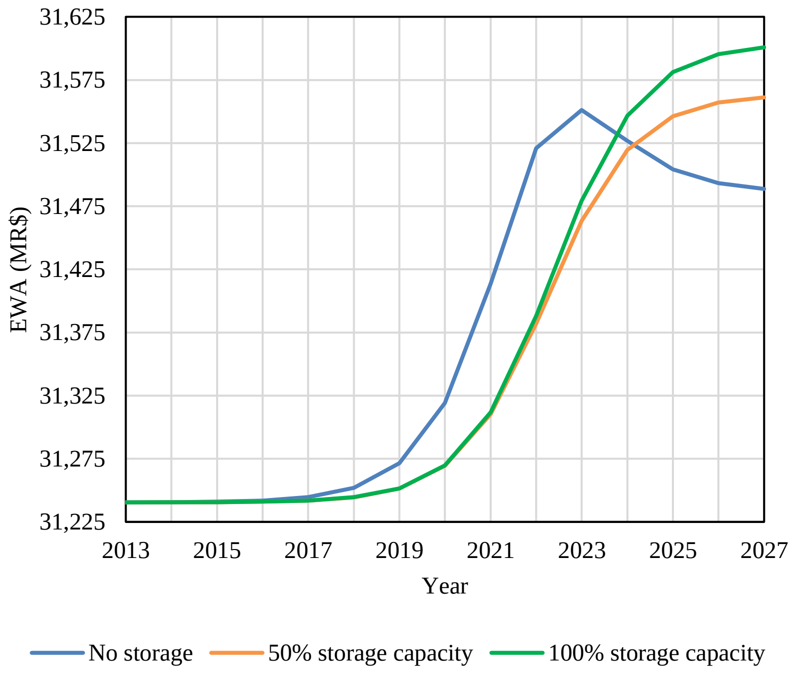

Figure 4.11. Socioeconomic welfare.

The consumer or prosumer surplus is illustrated in Figure 4.12. From the prosumers' point of view, ESSs are not particularly beneficial due to their high CAPEX. The decrease in battery costs or a greater difference between the off-peak and peak periods tariffs could enhance ESSs' feasibility. Alternatively, ESSs' feasibility could be enhanced by increasing the compensation policy parameter.

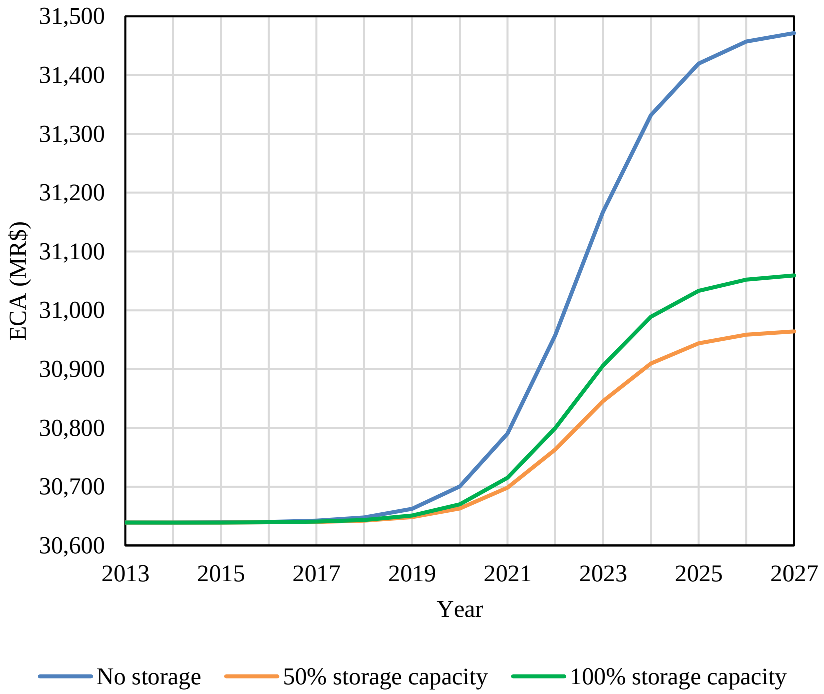

Figure 4.12. Consumer or prosumer surplus.

4.5.2 Policies to promote ESSs deployment

Section 4.5.1 demonstrated that ESSs were not particularly beneficial in this case study under the net metering policy. Hence, this section analyzes alternative policies to enhance ESSs' feasibility.

To overlap the ECA for Scenarios (1), (2), and (3), their compensation policy parameters should be $n = 1$, $n = 1.24$, and $n = 1.16$, respectively [13]. In this case, Scenarios (2) and (3) considerably influence EVA, as shown in Figure 4.13. However, they are still less detrimental to the DISCO than Scenario (1).

[13] It should be noted that it is not appropriate to increase the compensation policy parameter for Scenario (1) since it would result in negative EVA.

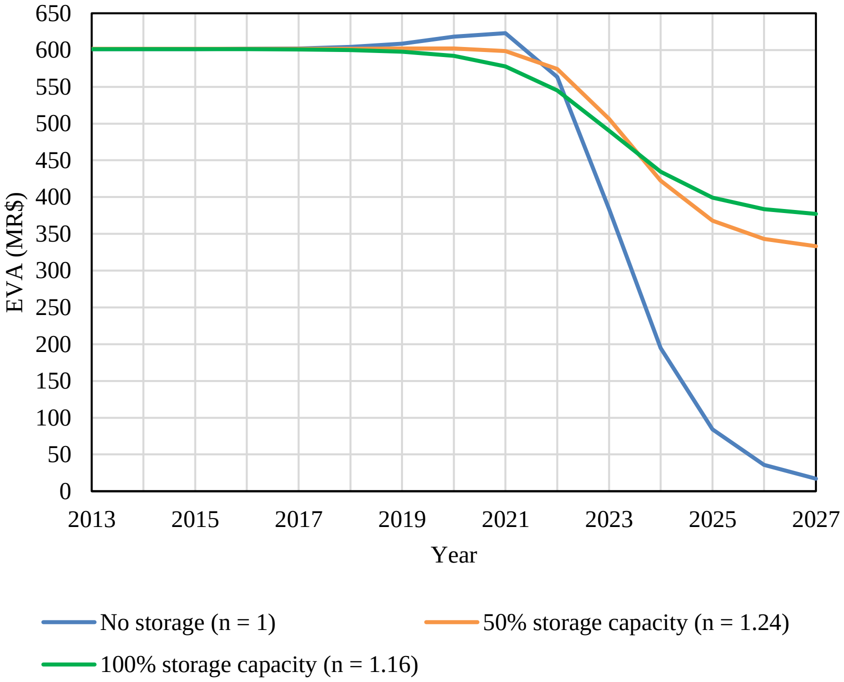

Figure 4.13. DISCO surplus for alternative compensation policy parameters.

The alternative compensation policy parameters substantially boost socioeconomic welfare, as per Figure 4.14. The PEI for Scenarios (1), (2), and (3) are 129.9 MR$, 206.0 MR$, and 206.0 MR$, respectively, highlighting that the regulatory agency plays an essential role in promoting the integration of new technologies.

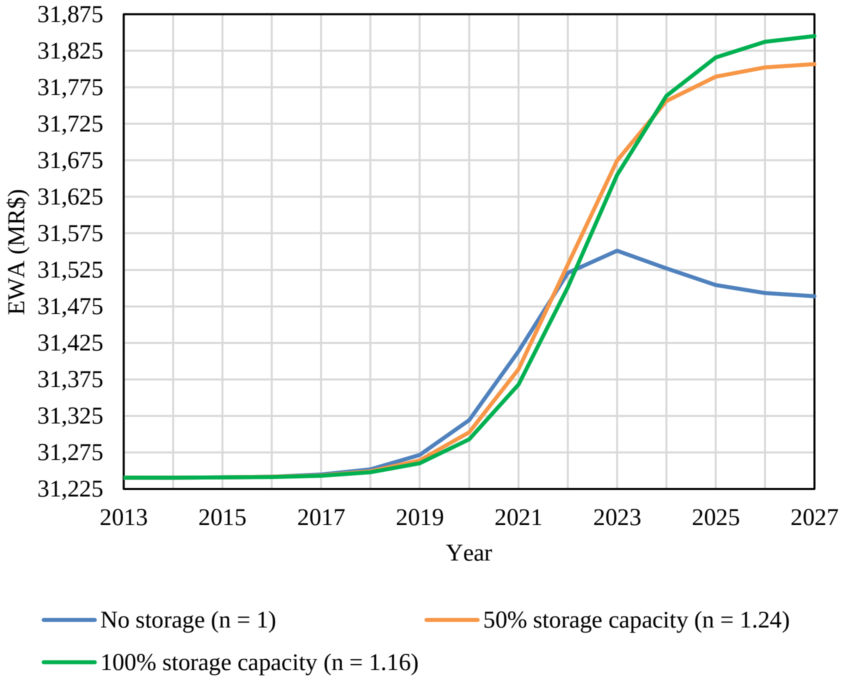

Figure 4.14. Socioeconomic welfare for alternative compensation policy parameters.

This chapter achieved objective (*ii*) and answered RQ2.

4.6 Summary of results and analysis

An analysis of the effects of DERs on the regulated electricity market was conducted in this chapter. The results demonstrated that:

- Under the current regulatory framework in Brazil (compensation scheme with relatively high compensation) DERs tend to decrease the DISCO's costs and revenue, but the decrease in revenue tends to be more influential than the decrease in costs, meaning that DERs are detrimental to the DISCOs;
- If DERs penetration increases indiscriminately and no action is taken, the death spiral process takes place, in which it becomes increasingly difficult to guarantee the FEE state for the DISCO (EVA ≥ 0) due to recurring and excessive tariff increases;
- Given that the DISCO analyzed in Section 4.3 presented positive EVA, a reasonable DERs integration would still maintain the FEE state;
- In the context of increasing DERs integration, changing the compensation is a fairer approach than changing the tariff since the compensation only affects prosumers;
- In the context of TOU rates implementation, energy shifting incentives can be implemented based on the concept of energy economic utility;
- ESSs can be beneficial in decreasing energy loss;
- Conventional DG systems tend to be more beneficial in the short term, whereas DG systems with ESSs tend to be more beneficial in the long term since the latter is more expensive, causing the BDM installed capacity estimation to be "delayed";
- The role of the regulatory agency is essential in responsibly/effectively promoting the integration of emerging DERs, such as ESSs.

5 THE TAROT MODEL FROM A HOLISTIC PERSPECTIVE

This chapter applies the TAROT model from a holistic perspective in the context of DG integration, assuming socioeconomic and environmental indicators. ESSs and TOU rates are disregarded since the goal is to assess the impacts of a recently implemented DG regulation in Brazil (OL). After analyzing the impacts of the OL, MOO is used to introduce optimal regulatory solutions. Then, the MOO problem is extended to include CBMs.

5.1 LCA

Environmental issues are introduced into the model based on an LCA. Essential queries concerning the goal and scope definition are as follows:

- The idea is to quantify the GWP of DG and of conventional or centralized generation since such data is used in the proposed model. GWP is addressed since it is generally regarded as the most worrying environmental impact category. GWP is formally defined as "the cumulative radiative forcing, both direct and indirect effects, over a specified time horizon resulting from the emission of a unit mass of gas related to some reference gas" [102]. In more general terms, greenhouse gases warm the earth by absorbing energy and "trapping" the energy in the atmosphere. Different gases differ in their ability to absorb energy. Thus, GWP quantifies the amount of energy the emissions of 1 ton of a gas will absorb over a given period compared with the emissions of 1 ton of CO_2 [102]. Although GWP is addressed, it is noteworthy that other impact categories disregarded herein are also important;
- To ensure an unbiased assessment, it is considered that conventional or centralized generation must be used in case of reduced demand for DG systems (*e.g.*, OL). On the other hand, in case of increased demand for DG systems, a reduction in centralized generation requirements is assumed. It is emphasized that the necessary centralized generation is assumed to be based on the average Brazilian electricity matrix, including hydro, wind, natural gas, biomass, PV, nuclear, coal, and oil;
- The Intergovernmental Panel on Climate Change (IPCC) 2013 LCIA method is applied since it is widely recognized and focuses on GWP. Moreover, GWP 100a is addressed, *i.e.*, over 100 years;
- A functional unit of 1 TWh of generated electricity is assumed;
- The software OpenLCA is used due to its wide recognition and open-source characteristics;
- The transportation of technologies and the usage phase of electricity generation are adapted to the Brazilian context to conform with the case studies. Given that distributed PV systems account for more than 99% of connections in Brazil [100], they are the subject of study;
- Multi-crystalline silicon (multi-Si) modules are considered since they are among the most deployed;

• Modules and inverters are the two main components of the PV system concerning environmental impacts since their manufacturing is resource-intensive [103]. Therefore, DC cables and installation materials are addressed as cut-off criteria;

• Disposal or recycling is not considered since the system's lifetime is much longer than the forecast horizon.

Based on the problem definition, the GWP is modeled by Equation (5.1):

$$GWP(t) = A_G E_G(t) + A_C(t)[E_{GB}(t) - E_G(t)] \quad (5.1)$$

where: A_G is the LCA results for DG and $A_C(t)$ is the LCA results for centralized generation. $E_G(t)$ is the generated electricity from DG and $E_{GB}(t)$ is the benchmark generated electricity from DG, which is calculated assuming the original payback time, *i.e.*, assuming the net metering scheme and a constant regulated tariff, in Equation (4.17).

Figure 5.1 illustrates the product system, which includes the necessary processes for manufacturing, transporting, and deploying the PV modules and inverters based on the gathered LCI. The cradle-to-gate LCI of the PV modules and inverters were obtained from Yang *et al.* [104] and Tschümperlin *et al.* [105], respectively. Manufacturing in China and Germany is assumed for the PV modules and inverters, respectively, since these regions present significant manufacturing of such technologies and reliable LCI data. It is noteworthy that considering the importation of technologies is a proper approach since Brazil is still incipient in this regard.

The processes adapted to the Brazilian context depend on particular local characteristics. Specifically, the amount of peak sun hours (PSH) and technology transportation requirements vary depending on the location (Brazil is a very large country). Hence, the LCI of each concession area differs due to variations in PSH and transportation requirements.

Concerning conventional electricity generation, the Ecoinvent database 3.7.1 [106] was used since it presents processes that represent the Brazilian electricity matrix. However, the electricity matrix available in such a database dates back to 2014. Thus, it was updated to increase the accuracy of the LCA, as per Figure 5.2. Moreover, electricity matrix variation over time was also accounted for, for enhanced accuracy. Given that only data from 2021 and 2030 were available, a linear variation for the electricity matrix was considered. Lastly, the Ecoinvent database was also used for background processes.

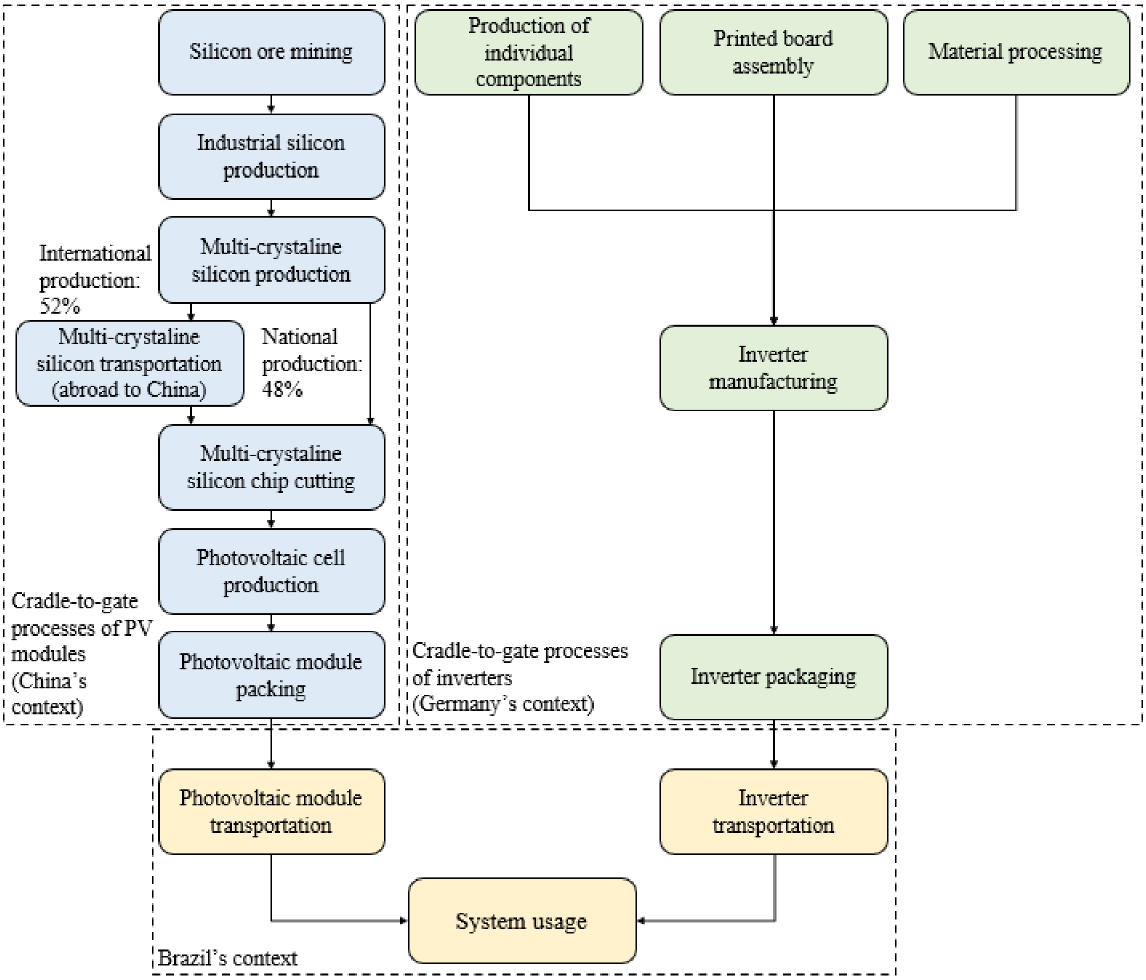

Figure 5.1. Product system for PV distributed generation.

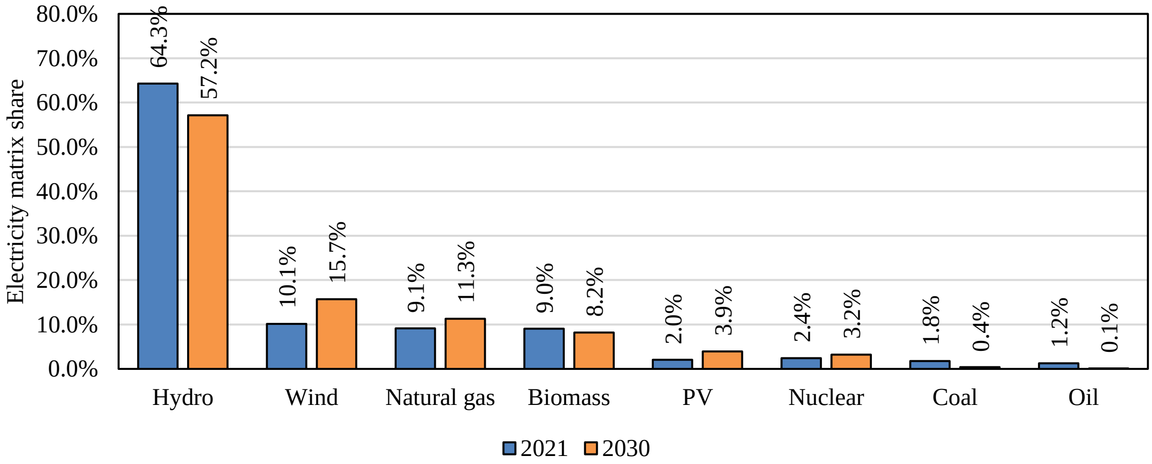

Figure 5.2. Brazilian electricity matrix for quantifying the environmental impacts of centralized generation (data from [107], [108]).

5.2 Holistic analysis of the impacts of the OL

In this section, the TAROT, BDM, and LCA are used to holistically analyze the OL impacts on 35 Brazilian concession areas. The assumed TAROT model is very similar to that presented in Chapter 4, except that the variables are not separated into indexes O, I, and P since flat electricity pricing is addressed. Given the similarity of the model, it is not presented here, but details can be found in Paper *f*.

The procedure conducted here is similar to the algorithm previously presented in Figure 4.7, with the addition of more aspects, including environmental and tariff considerations. The simulations are conducted until 2030 for all concession areas for two main reasons: (*i*) in general, the integration of DG systems flattens significantly past 2030, and (*ii*) thus far, the OL does not specify its compensation scheme past 2030 (calculation procedure).

The goal is to analyze the impacts of the OL compared to the net metering scheme (reference scenario). Although the PH proposals were not approved, the results for the PH - alternatives 1 ($n = 73\%$) and 5 ($n = 43\%$) are also included for comparison's sake. Alternatives 1 and 5 are the PH's best and worst options from the prosumers' point of view, respectively.

For better contextualization, Table 5.1 describes important information concerning the assessed concession areas, and Figure 5.3 illustrates an associated map.

TABLE 5.1. ASSESSED CONCESSION AREAS.

Concession area	State	Electricity consumption (TWh/year) [109]	Generation from DG (TWh/year) [100]	Regulated tariff (MR$/TWh) [109]	Average monthly income per family (MR$) [110]
COELBA	BA	19.64	0.444	806.7	965
ENEL CE	CE	12.14	0.450	601.5	1,028
EDP ES	ES	7.40	0.170	768.9	1,347
ELFSM	ES	0.55	0.020	836.1	1,347
CEMAR	MA	7.58	0.240	620.7	676
CEMIG-D	MG	31.43	2.149	739.1	1,314
ENERGISA MG	MG	1.38	0.097	846.6	1,314
ENERGISA MS	MS	5.48	0.342	740.7	1,488
ENERGISA MT	MT	9.40	0.871	1,013.7	1,401
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	1,508
COPEL-DIS	PR	22.67	0.529	722.4	1,508
FORCEL	PR	0.04	0.003	917.7	1,508
ENEL RJ	RJ	11.18	0.278	889.4	1,723
ENERGISA NF	RJ	0.32	0.004	875.7	1,723
LIGHT	RJ	25.26	0.149	720.7	1,723
COSERN	RN	5.34	0.290	746.3	1,077

Concession area	State	Electricity consumption (TWh/year) [109]	Generation from DG (TWh/year) [100]	Regulated tariff (MR$/TWh) [109]	Average monthly income per family (MR$) [110]
DEMEI	RS	0.15	0.006	736.3	1,759
ELETROCAR	RS	0.18	0.013	784.5	1,759
HIDROPAN	RS	0.09	0.006	863.6	1,759
MUX ENERGIA	RS	0.07	0.002	684.8	1,759
RGE SUL	RS	16.78	0.983	751.5	1,759
UHENPAL	RS	0.09	0.003	688.1	1,759
CELESC-DIS	SC	18.34	0.250	707.1	1,632
COPERALIANÇA	SC	0.21	0.002	644.0	1,632
EFLJC	SC	0.02	0.000	721.2	1,632
EFLUL	SC	0.04	0.002	1,101.6	1,632
ENERGISA SE	SE	3.16	0.069	671.8	1,028
SULGIPE	SE	0.35	0.004	636.9	1,028
CPFL Paulista	SP	23.59	0.685	793.4	1,814
AES Eletropaulo	SP	35.80	0.068	667.4	1,814
ELEKTRO	SP	12.75	0.357	745.5	1,814
ENERGISA TO	TO	2.59	0.125	787.7	1,060

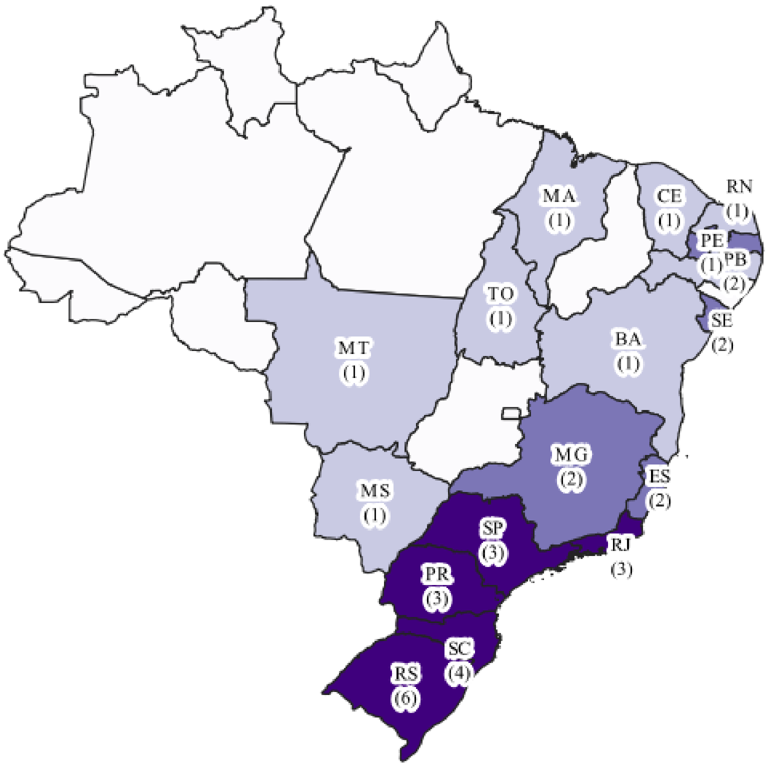

Figure 5.3. Map of the assessed concession areas.

Although 35 concession areas are analyzed, first, a more detailed analysis is performed for a specific concession area (CPFL Paulista) so that the model's behavior is clarified. CPFL Paulista was selected due to the high economic development and DG potential of São Paulo. Arguably, CEMIG-D would be a suitable DISCO for detailed analysis due to its high DG integration. However, given that the OL safeguards the rights of prosumers who installed their systems before 2023 (the net metering scheme is maintained in such cases), the OL impacts in CEMIG-D's concession area are partially mitigated. Therefore, CEMIG-D is analyzed along with the other 34 concession areas in Section 5.2.2.

5.2.1 Detailed results for CPFL Paulista

The impacts of implementing the OL in CPFL Paulista are illustrated in Figure 5.4. The regulated electricity tariff is assumed to be constant since the goal is to assess the impacts of the OL in the context of the absence of external regulatory interventions, except in Figure 5.4. *d*), where the tariff impact is analyzed. Essential outcomes are as follows:

- Generated electricity from DG (Figure 5.4. *a*)): the OL is expected to decrease the generated electricity from DG significantly due to its higher payback time compared to the net metering policy and, consequently, its inferior economic incentives for investing in DG systems.
- DISCO surplus (Figure 5.4. *b*)): DG integration significantly decreases EVA for net metering policy and for the OL. However, the decrease for the OL is less pronounced. Moreover, the net metering policy results in a negative EVA after 2026. Additionally, an oscillatory behavior is verified in the OL curve due to its variable compensation over time, implying changes in the DISCO's revenue. Such a behavior is also verified in other graphs.
- Socioeconomic welfare (Figure 5.4. *c*)): DG integration substantially increases EWA under the net metering and under the OL, but the latter results in lower EWA. Moreover, the EWA for the OL is practically constant towards the end of the simulation period since there is less DG integration while compensation continues to decrease.
- Regulated electricity tariff (Figure 5.4. *d*)): DG integration increases the tariff notably for the net metering policy in the long term due to the decreasing EVA tendencies. The OL decreases the tariff significantly compared to the net metering policy, but only in the medium or long term, *i.e.*, when compensation reduces considerably.
- Global warming potential (Figure 5.4. *e*)): a significant difference is verified between the policies due to the higher GWP for centralized generation compared to distributed PV generation. Given that alternative policies other than the net metering scheme seek to implement lower compensation for the electricity injected into the grid, they imply lower demand for DG systems and consequently more centralized generation requirements, thus resulting in higher GWP. In particular, the results show that centralized generation is currently 78% more hazardous in the CPFL Paulista's concession area, even though Brazil is known for having a renewable electricity matrix mainly comprising hydroelectric power plants (64%). Specifically, emissions of distributed PV generation are estimated at 57.95 g CO_2-eq for CPFL Paulista, whereas

emissions for centralized generation are estimated at 102.92 g CO_2-eq in 2021 and 115.30 g CO_2-eq in 2030. The increase in emissions for centralized generation is due to the rising share of generation from natural gas. An increase in emissions has also been verified in previous studies [111]. Such an increase results in Figure 5.4. *e*) flattening less intensely than the other graphs towards the end of the simulation.

The discussions presented above are also valid for the PH scheme. However, the impacts are more pronounced in this case due to its lower compensation, especially for alternative 5.

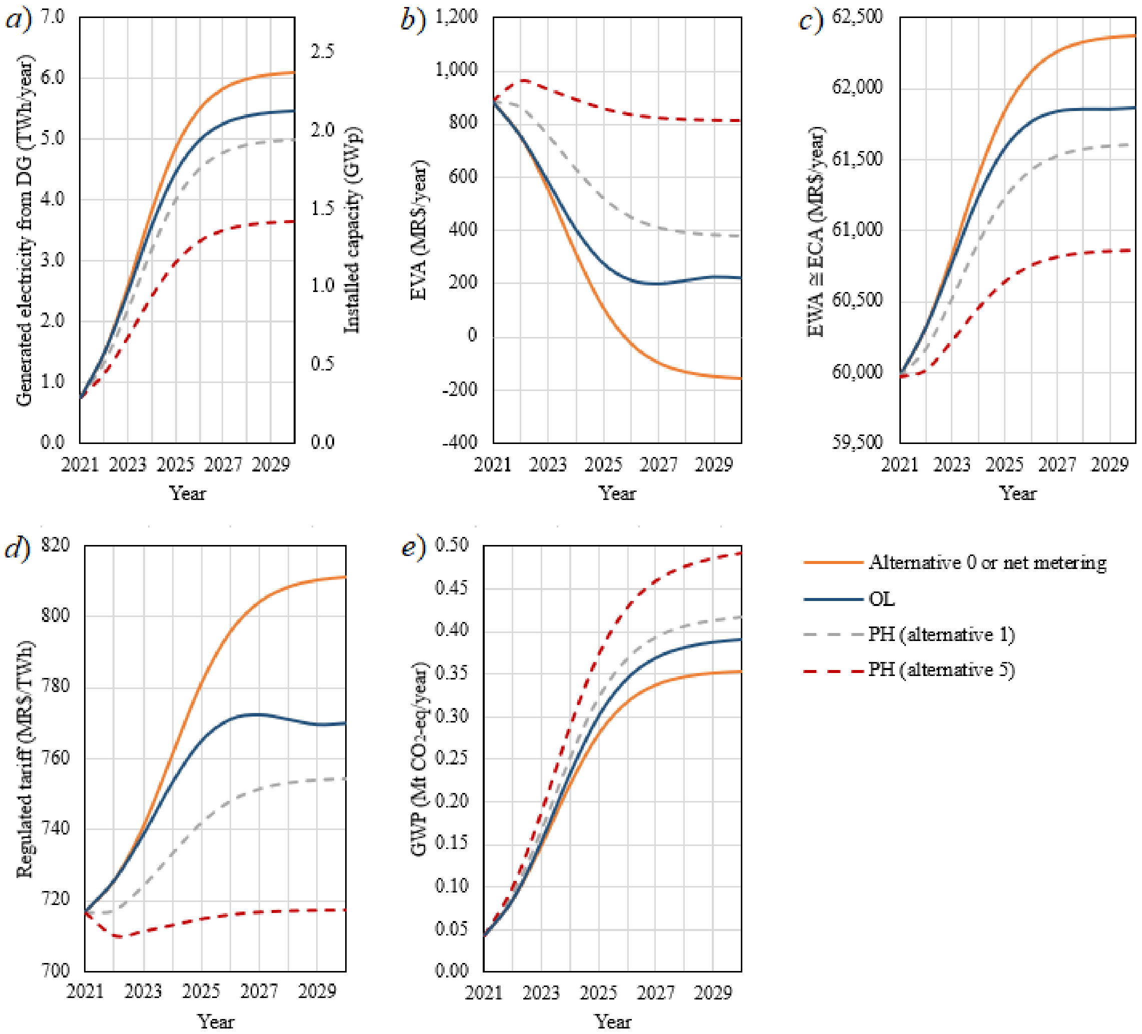

Figure 5.4. OL impacts on CPFL Paulista's concession area in terms of *a*) generated electricity from DG, *b*) EVA, *c*) EWA, *d*) regulated electricity tariff, and *e*) GWP.

Table 5.2 presents the long-term OL impacts quantitatively. The undesirable impacts, *i.e.*, the variations in the generated electricity from DG, PEI, and GWP, are around –12%, whereas the desirable effect, *i.e.*, the variation in the regulated electricity tariff, is –5.1%. Additionally, Table 5.2 highlights the substantial negative consequences of the PH scheme.

TABLE 5.2. LONG TERM OL IMPACTS ON CPFL PAULISTA.

	Generated electricity from DG (%)	PEI (%)	Regulated tariff (%)	GWP (%)
OL	–10.5	–16.4	–5.1	–10.4
PH (alternative 1)	–18.2	–32.7	–7.0	–18.1
PH (alternative 5)	–40.0	–64.6	–11.5	–39.6

5.2.2 Long-term results for the 35 assessed concession areas

In this section, the OL consequences on the 35 assessed concession areas are presented. Only long-term results (2030) are addressed for simplicity's sake.

The ranking of the most affected concession areas by the OL in terms of generated electricity from DG is illustrated in Figure 5.5. Only the ten most affected concession areas are illustrated in the graphs not to impair the visualization. The results for all concession areas are available in [112]. Contrary to common belief, results demonstrate that CEMIG-D, which is currently the concession area with the highest DG installed capacity, will not be the most affected in terms of generated electricity. Instead, AES Eletropaulo tends to be more affected for four main reasons: (*i*) AES Eletropaulo is a larger concession area in terms of electricity consumption, *i.e.*, it presents a higher market potential for DG integration (m_p), (*ii*) AES Eletropaulo is a wealthier concession area, which increases its maximum market fraction (m_{mf}) (*iii*) AES Eletropaulo presents a higher share of residential DG (58%). Thus, its share of self-consumption (l) is lower, implying that prosumers are more reliant on the compensation for the electricity injected into the grid, and (*iv*) only potential new prosumers are sensitive to the OL concerning the decision to purchase or not DG systems. Hence, CEMIG-D's current substantial DG installed capacity will be maintained regardless of regulatory changes.

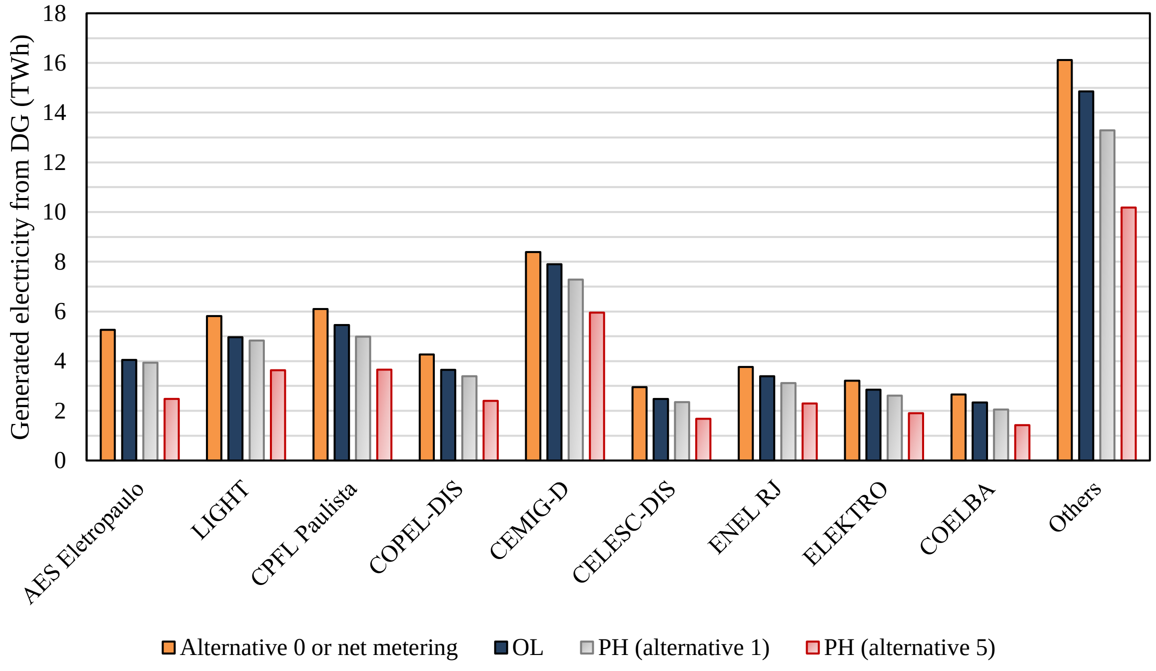

Figure 5.5. Ranking of the most affected concession areas in 2030 in terms of the generated electricity from DG (TWh).

It is important to assess the relative OL impacts (percentage terms) to consider the interests of small-scale concession areas. Thus, a ranking similar to Figure 5.5 is illustrated in Figure 5.6, but in percentage terms (the net metering policy is represented as 1 per unit). Small-scale concession areas are also significantly affected. It is important to mention that although most small-scale concession areas currently have incipient DG installed capacities, they exhibit future potential, which will be partially forfeited.

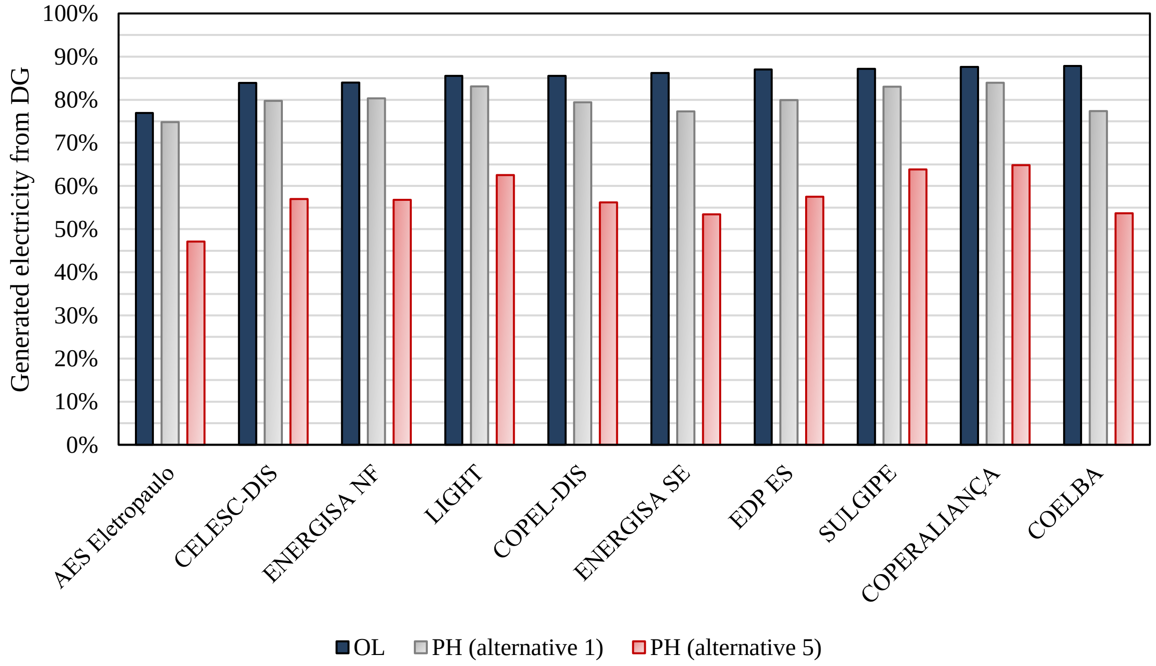

Figure 5.6. Ranking of the most affected concession areas in 2030 in terms of generated electricity from DG (%).

A ranking of the most affected concession areas in terms of the PEI is illustrated in Figure 5.7. CPFL Paulista is the most affected, followed by CEMIG-D, since the OL states that only DG systems deployed after Jan/2023 are subject to regulatory changes. Thus, CEMIG-D's current substantial DG installed capacity is not subject to regulatory changes. Nevertheless, impacts on CEMIG-D's concession area are relatively high (second) due to its extensive DG potential (high tariff and PSH), which is partially forfeited after the OL.

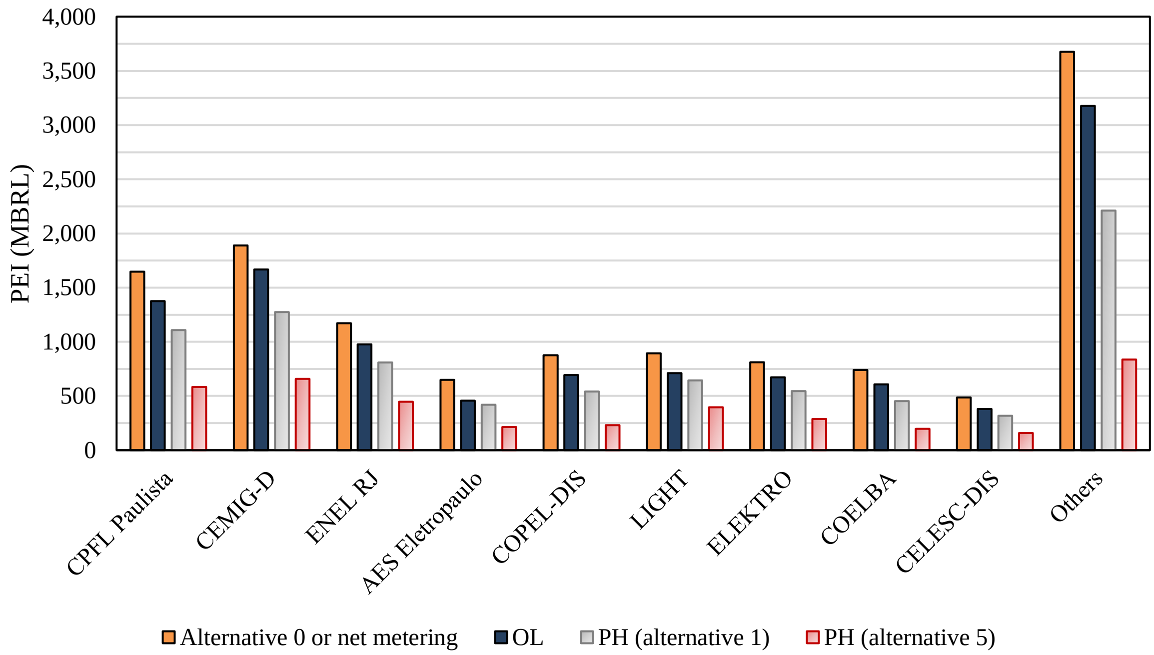

Figure 5.7. Ranking of the most affected concession areas in 2030 in terms of the PEI.

A ranking of the most affected concession areas in terms of the regulated tariff is illustrated in Figure 5.8. Different from the other rankings, Figure 5.8 shows OL benefits in the form of reduced tariffs. ENEL RJ is the most benefited since its tariff decreases the most. Interpreting these results is not so simple since tariffs are calculated numerically. However, the following factors contribute to the considerable decrease in ENEL RJ's tariff: (*i*) ENEL RJ has a high tariff (4^{th} highest) 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 estimation), indicating notable penetration levels relative to its market size. Item (*ii*) is mainly why small-scale concession areas also benefit significantly from tariff decreases caused by the OL, as shown in Figure 5.8.

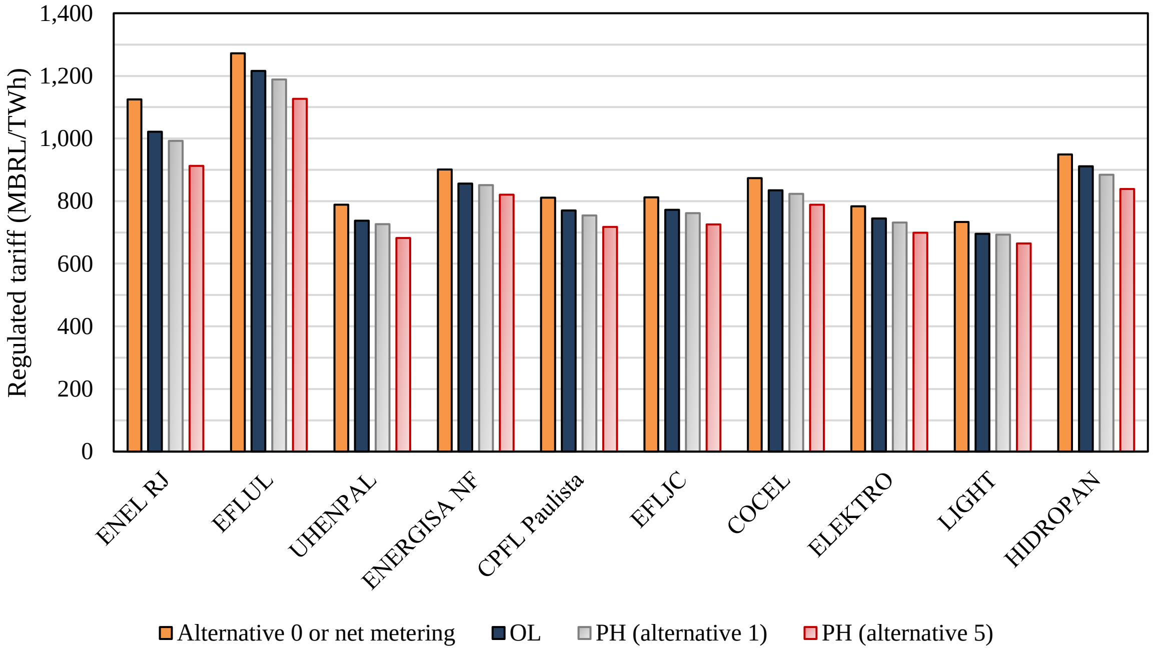

Figure 5.8. Ranking of the most affected concession areas in 2030 in terms of regulated electricity tariffs.

Before presenting the ranking of the most affected concession areas in terms of GWP, it is essential to assess the LCA results for distributed PV systems in g CO_2-eq/kWh (Figure 5.9). Performing an LCA for each concession area is important since emissions per kWh might vary significantly. A thorough literature review of LCA for PV systems [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], as depicted in Figure 5.10, shows that the results obtained are consistent with previous research on the topic. All results are presented in terms of average. As shown in Figure 5.10, Constantino *et al.* [50] conducted an LCA study most similar to this thesis, as it was also conducted within the Brazilian context and assumed the use of multi-Si modules. Finally, the ranking of the most affected concession areas in terms of GWP is given in Figure 5.11. The results show that AES Eletropaulo is the most affected.

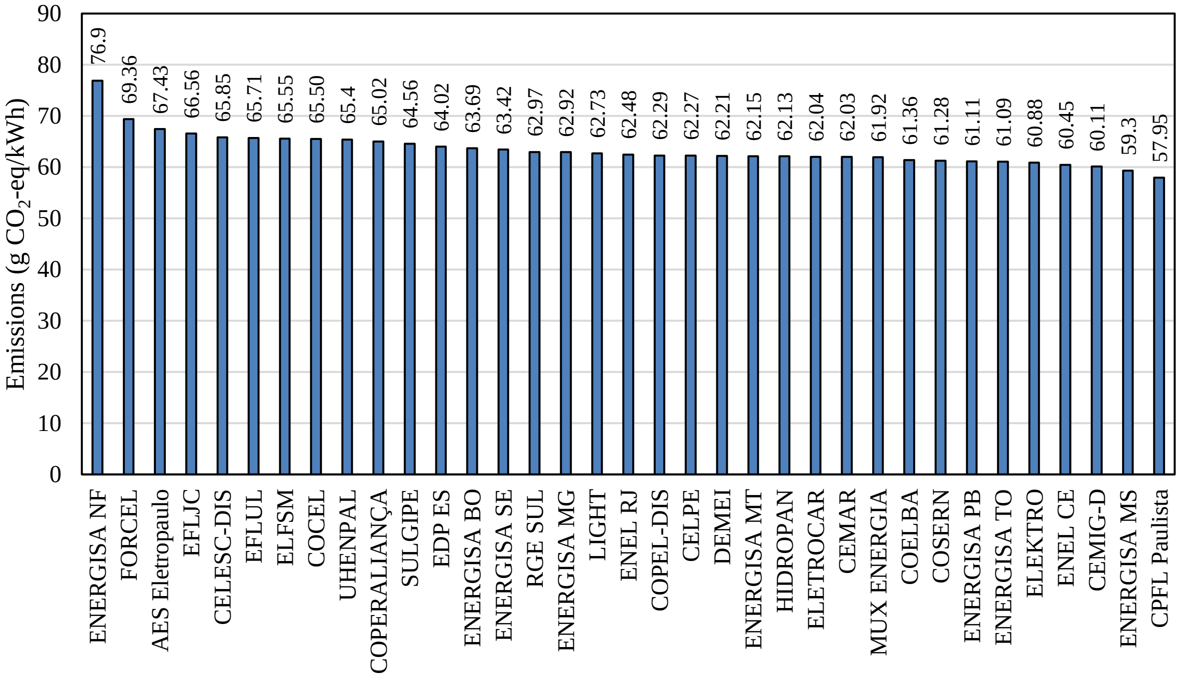

Figure 5.9. LCA results.

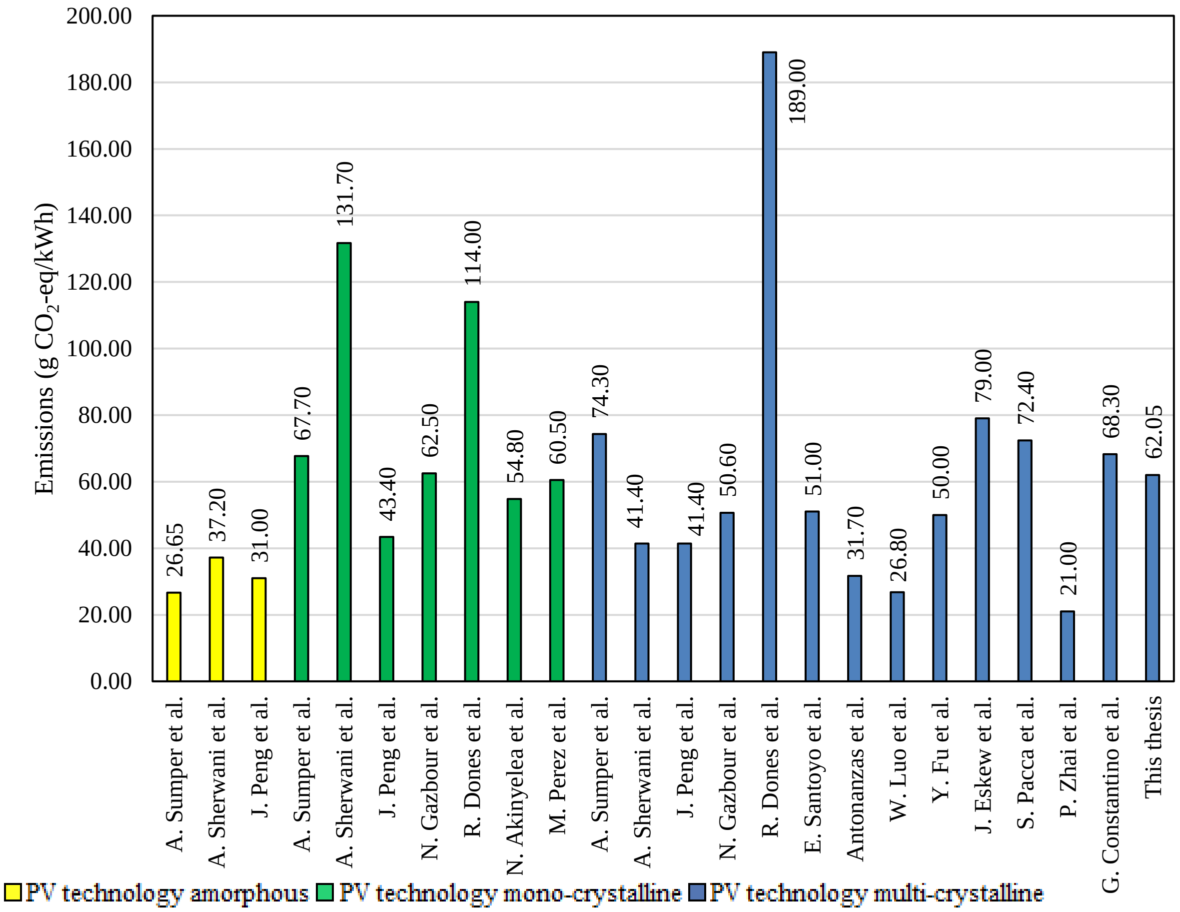

Figure 5.10. Comparison between the obtained LCA results and previous research on the topic.

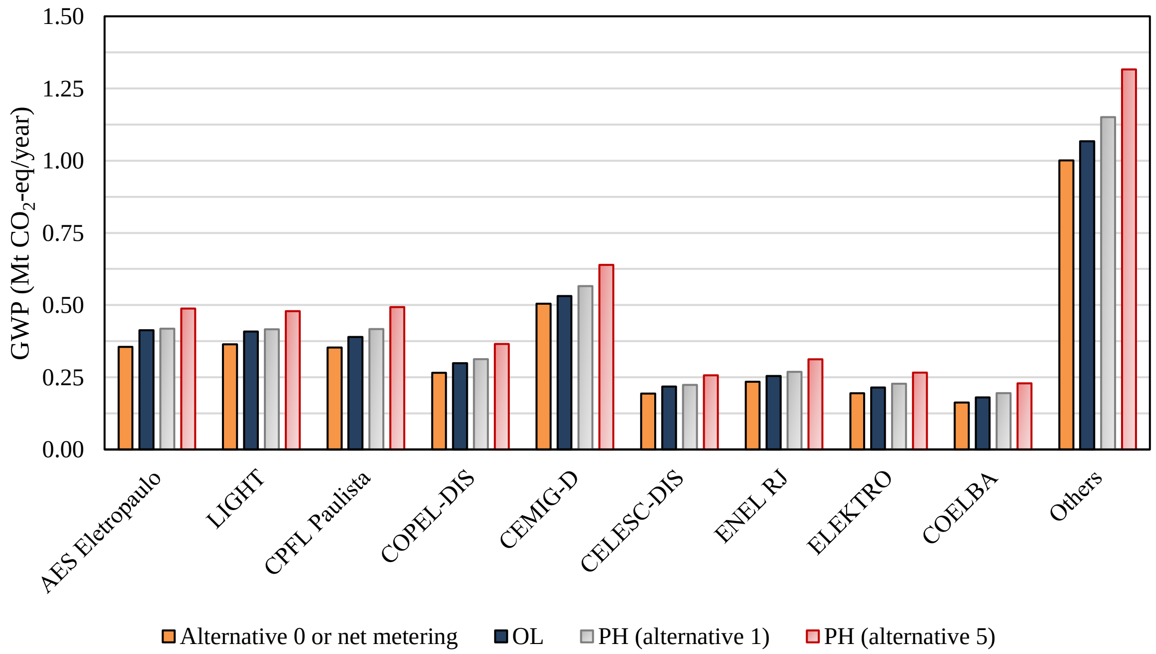

Figure 5.11. Ranking of the most affected concession areas in 2030 in terms of GWP.

Another important outcome is the OL impacts per state. The results do not represent the overall impacts in each state since only 35 concession areas were analyzed. Nevertheless, such an analysis provides meaningful conclusions.

A map of the OL impacts in terms of generated electricity from DG is illustrated in Figure 5.12. *a*), where São Paulo, which was 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 due to 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 due to the presence of only one large-scale concession area in Minas Gerais compared to three in São Paulo, resulting in a lower m_p for the former state.

A map of the OL impacts in terms of the PEI is illustrated in Figure 5.12. *b*) (São Paulo represented at 1 per unit). Similar to Figure 5.12. *a*), the most affected states are located in the Southeast region. However, the difference between São Paulo and Minas Gerais is lower, given the extensive DG potential in Minas Gerais.

A map of the OL effects in terms of regulated tariffs is illustrated in Figure 5.12. *c*). The tariff for each state is calculated based on a weighted average (the weights are the electricity consumption in the concession areas). Different from the other maps, Figure 5.12. *c*) shows the OL benefits in the form of reduced tariffs. Rio de Janeiro is represented at 1 per unit since it benefits the most (greatest tariff reductions). On the other hand, São Paulo does not benefit substantially due to its massive electricity consumption. Therefore, the E_G/E ratio for São Paulo is relatively low.

Finally, a map of the OL impacts in terms of GWP is shown in Figure 5.12. *d*) (São Paulo is represented at 1 per unit).

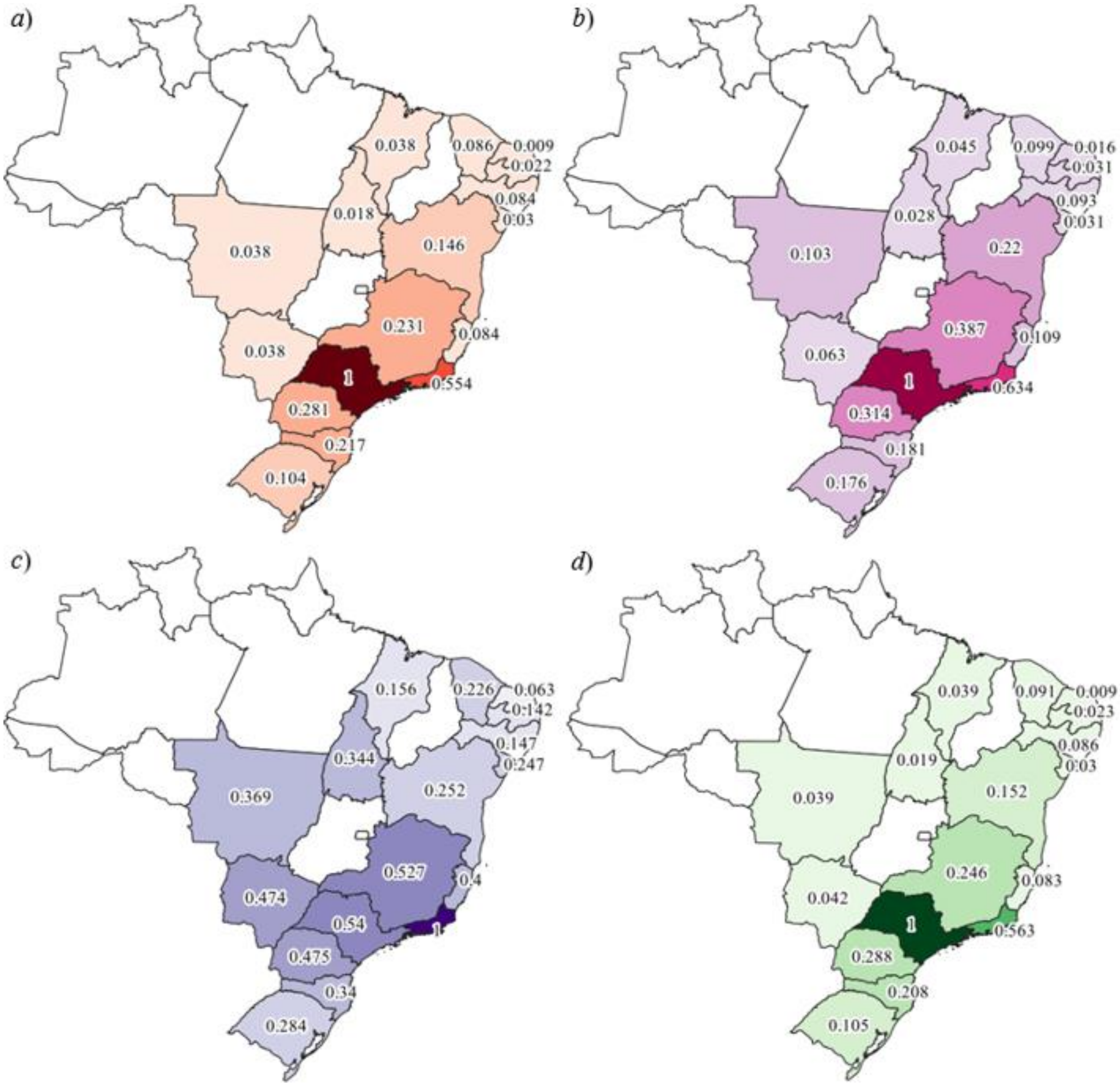

Figure 5.12. Map of the OL impacts in 2030 in terms of *a*) generated electricity from DG, *b*) PEI, *c*) regulated electricity tariffs, and *d*) GWP.

After assessing the OL impacts in each concession area and state, it is essential to calculate the overall impacts. In this case, all impacts are summed except for regulated tariffs, where a weighted average is conducted. The results are shown in Figure 5.13 and Table 5.3. The OL successfully mitigates tariff increases and reduces social inequality. However, there are 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 [113]. Therefore, the long-term OL impacts on the generated electricity from DG are around 1.4% of all Brazil's electricity consumption (calculated based on 2020 demand). Regarding

GWP, Brazil's electricity generation carbon footprint corresponded to 116 Mt CO_2-eq/year in 2021 [111]. Hence, the long-term OL impacts on GWP are around 0.3% of the country's emissions from electricity generation (calculated based on the 2021 footprint). Brazil's electricity consumption and carbon footprint from electricity generation were 11.8% and 7.5% of those in the USA, respectively [114]. Thus, OL impacts are about 0.2% and 0.02% of the USA's electricity consumption and carbon footprint on electricity generation, respectively. Environmental impacts relative to those of the USA are not very significant, given Brazil's high share of renewables.

It should be emphasized that while reductions in the compensation for the electricity injected into the grid are necessary in Brazil, the OL defined the compensation empirically, without the application of well-defined methods.

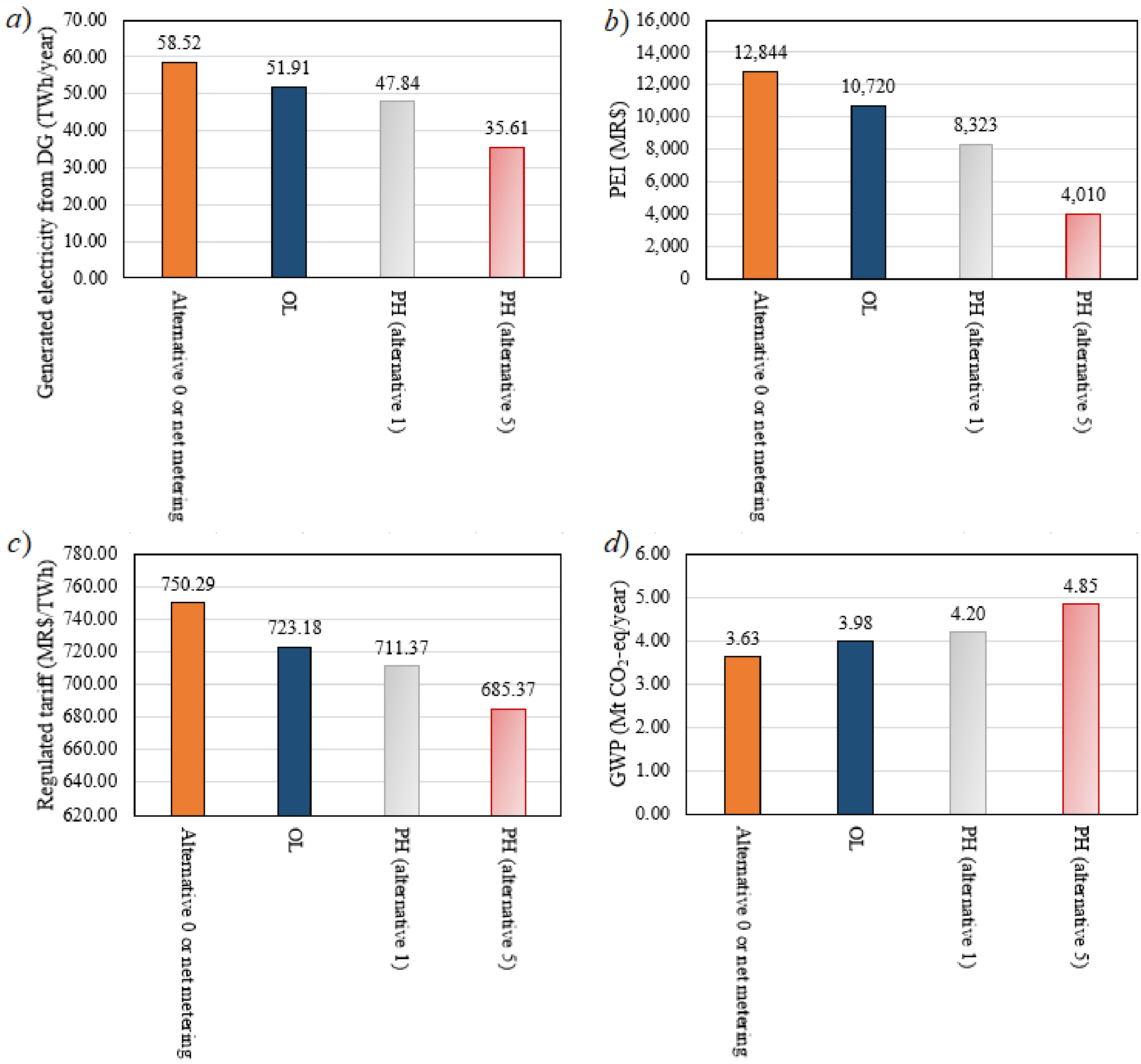

Figure 5.13. OL impacts on the equivalent concession area in terms of *a*) generated electricity from DG, *b*) PEI, *c*) regulated electricity tariff, and *d*) GWP.

TABLE 5.3. OL IMPACTS ON THE EQUIVALENT CONCESSION AREA.

		Generated electricity from DG	PEI	Regulated tariff	GWP
OL	Absolut impact	–6.60 (TWh/year)	–2,123 (MBRL)	–27.11 (MBRL/TWh)	0.346 (Mt CO_2-eq/year)
	Relative impact (%)	–11.3	–16.5	–3.6	9.5
PH - alternative 1	Absolut impact	–10.67 (TWh/year)	–4,520 (MBRL)	–38.92 (MBRL/TWh)	0.565 (Mt CO_2-eq/year)
	Relative impact (%)	–18.2	–35.2	–5.2	15.6
PH - alternative 5	Absolut impact	–22.91 (TWh/year)	–8,834 (MBRL)	–64.92 (MBRL/TWh)	1.214 (Mt CO_2-eq/year)
	Relative impact (%)	–39.2	–68.8	–8.7	33.4

5.3 Holistic and optimal regulatory solutions based on MOO

In this section, a holistic and optimal regulatory framework for DG is presented based on the TAROT, BDM, LCA, and MOO. A scalarization MOO problem is proposed, in which the MOO problem is solved multiple times, assuming varying weights for the objectives. The goal is to maximize socioeconomic welfare created by the market and minimize the GWP and regulated tariffs. Alternatively, minimizing tariffs can be interpreted as maximizing electricity affordability for consumers. Moreover, minimizing GWP aims to assist the energy transition process and limit global temperature growth (naturally, this must be a joint effort, from numerous decision-makers/countries so that there are significant differences at a global level). To avoid dealing with three-dimensional analyses that are heavily time-consuming and intricate to interpret, socioeconomic welfare and GWP are combined into one objective since they are concurrent objectives to some extent, *i.e.*, if one objective improves the other also tends to improve and vice versa, and both can be represented in monetary terms. Specifically, GWP is initially quantified in Mt CO_2-eq (as per the applied LCIA method - IPCC 2013) and converted to MR$ based on the typical social cost of carbon. The social cost of carbon is an estimation of the economic damages associated with GWP (assumed as 783 MR$/Mt CO_2-eq, as per Paper *h*). The conversion from Mt CO_2-eq (original LCA results) to MR$ (economic damages associated with GWP) is done by a simple multiplication (social cost of carbon × original LCA results). Additionally, the applied TAROT model is equivalent to that of Section 5.2. Further details can be found in Paper *h*.

The two objectives, called performance indexes (PEI), are defined as Equations (5.2) and (5.3):

$$PEI[EWA(t), CGWP(t)] = EWA(t_0) - \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} EWA(t)dt - CGWP(t_0) + \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} CGWP(t)dt \quad (5.2)$$

$$PEI[T(t)] = -T(t_0) + \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} T(t)dt \quad (5.3)$$

where: t_0 and t_1 are the initial and final simulation years, respectively. $EWA(t)$ is socioeconomic welfare, calculated by Equation (4.14). $CGWP(t)$ is the cost of global warming potential, calculated by Equation (5.1) multiplied by the typical social cost of carbon. $T(t)$ is the regulated electricity tariff. The signs in Equations (5.2) and (5.3) were assigned so that minimization is considered in the MOO problem.

The original payback time equation is intricate to implement in mathematical programming problems. Hence, the payback time is modeled in a simplified manner by Equation (5.4):

$$P_{BT}(t) = \frac{P_{BT}(t_0)}{\frac{1}{\delta}\sum_{\Phi=t}^{\delta}\left\{[l + (1-l)n(\Phi)]\frac{T(\Phi)}{T(t_0)}\right\}} \quad (5.4)$$

where: $P_{BT}(t_0)$ is the payback time for the market's initial conditions (without changes in the design variables). $T(t_0)$ is the current electricity tariff and δ is an adjustable scalar responsible for defining the time frame in which changes in the design variables influence investments in DG. One should set δ close to the expected payback time for Equation (5.4) to be reasonably accurate. The case studies assume $\delta = 3$ years.

Finally, the MOO problem is proposed in Equation (5.5):

Objective function:

$$\min_{T(t),n(t),\forall t\in\{t_0,\dots,t_1\}} \left\{\frac{\alpha}{z_{N1} - z_{U1}} PEI[EWA(t), CGWP(t)] + \frac{1-\alpha}{z_{N2} - z_{U2}} PEI[T(t)]\right\} \quad (5.5.1)$$

Subject to:

Equations (4.4), (4.6), (4.7), (4.12), (4.13), (4.14), (4.16), (4.17), (4.18), and (5.4),	$\forall\, t \in \{t_0, \dots, t_1\}$	
Equations (5.2) and (5.3)		
$EVA(t) \geq 0,$	$\forall\, t \in \{t_0, \dots, t_1\}$	(5.5.2)
$K_{Tl} \leq T(t) \leq K_{Tu},$	$\forall\, t \in \{t_0, \dots, t_1\}$	(5.5.3)
$K_{nl} \leq n(t) \leq K_{nu},$	$\forall\, t \in \{t_0, \dots, t_1\}$	(5.5.4)
$\chi_{Tl} \leq \frac{T(t)}{T(t-1)} \leq \chi_{Tu},$	$\forall\, t \in \{t_0 + 1, \dots, t_1\}$	(5.5.5)

$$\chi_{nl} \leq \frac{n(t)}{n(t-1)} \leq \chi_{nu}, \qquad \forall\, t \in \{t_0 + 1, \dots, t_1\} \qquad (5.5.6)$$

where: α and $(1-\alpha)$ are the weights assigned to functions 1 ($PEI[EWA(t), CGWP(t)]$) and 2 ($PEI[T(t)]$), respectively. z_{N1} and z_{N2} are the nadir points of functions 1 and 2, respectively, which are obtained by maximizing each function individually subjected to all constraints. z_{U1} and z_{U2} are the utopia points of functions 1 and 2, respectively, which are obtained by minimizing each function individually subjected to all constraints. The terms $1/(z_{N1} - z_{U1})$ and $1/(z_{N2} - z_{U2})$ are applied as normalization factors so that the two functions present the same order of magnitude. According to Grodzevich *et al.* [115], this is the most recommended form of normalization. The design variables are assumed to be $T(t)$ and $n(t)$, *i.e.*, the regulated electricity tariff and compensation policy for the electricity injected into the grid. Equation (4.4) concerns the revenue. Equation (4.6) represents the consumer or prosumer surplus. Equation (4.7) quantifies electricity consumption variations due to tariff variations. Equation (4.12) is associated with the DISCO surplus. Equation (4.13) corresponds to the optimal grid investment. Equation (4.14) represents socioeconomic welfare. Equations (4.16), (4.17), and (4.18) quantify the electricity generation from DG. Equation (5.4) models the payback time of investments in DG. Equation (5.2) is associated with the PEI of socioeconomic welfare and cost of global warming potential, whereas Equation (5.3) is associated with the PEI of the regulated tariff. Equation (5.5.2) is applied to avoid the DISCO bankruptcy. Equations (5.5.3) and (5.5.4) are applied to limit the regulated tariff and compensation policy for the electricity injected into the grid, respectively. Equations (5.5.5) and (5.5.6) are applied to avoid abrupt oscillations in the same variables.

The applied solving algorithm is represented in Table 5.4.

TABLE 5.4. SOLVING ALGORITHM.

Step	Logic
1	Gather the input data for a specific concession area
2	Set constraints
3	Assign: *(i)* $z_{U1} = \infty$; *(ii)* $z_{N1} = -\infty$; *(iii)* $z_{U2} = \infty$; *(iv)* $z_{N2} = -\infty$
4	Find nadir and utopia points for functions $PEI[EWA(t), CGWP(t)]$ and $PEI[T(t)]$ and update their values
5	Set objective function = (5.5.1)
6	Define α step
7	**For** each α step, where $0 \leq \alpha \leq 1$
8	Minimize objective function

Store the values of the objectives and of the design variables
End for

5.3.1 Case study

The proposed model was applied to fifteen Brazilian concession areas with significant DG potential, as detailed in Table 5.5 and Figure 5.14. Similar to Section 5.2, t_1 is assumed to be 2030. As boundaries for the design variables, one can assume $0.7T(2021) \leq T(t) \leq 1.3T(2021)$ and $0.7 \leq n(t) \leq 1$. The compensation is considered not to increase in relation to the initial year $n(2021) = 1$ to align with ANEEL's intentions for regulating the market. Moreover, variations of up to ±10% are allowed annually, *i.e.*, $\chi_{Tl} = \chi_{nl} = 0.9$ and $\chi_{Tu} = \chi_{nu} = 1.1$, aligning with the variations observed in practice in Brazil.

TABLE 5.5. ASSESSED CONCESSION AREAS.

	State	Electricity consumption (TWh/year)	Generation from DG (TWh/year)	Regulated tariff (MR$/TWh)
COELBA	BA	19.64	0.45	806.69
$ENEL_{CE}$	CE	12.14	0.43	601.47
EDP	ES	7.40	0.18	768.88
CEMAR	MA	7.58	0.25	620.71
CEMIG	MG	31.43	2.16	739.09
EMS	MS	5.48	0.34	740.69
EMT	MT	9.40	0.91	1013.67
EPB	PB	4.49	0.20	689.72
LIGHT	RJ	25.26	0.17	720.74
$ENEL_{RJ}$	RJ	11.18	0.32	889.45
RGE	RS	16.78	1.11	751.53
ESE	SE	3.16	0.07	671.82
ELEKTRO	SP	12.75	0.36	745.50
ELETROPAULO	SP	35.80	0.06	667.37
CPFL	SP	23.59	0.76	793.37

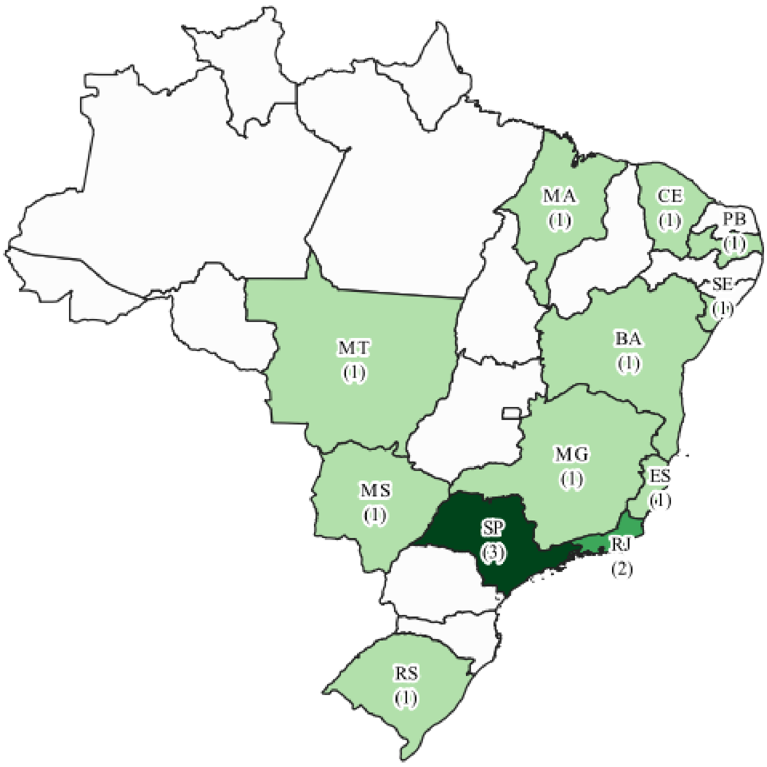

Figure 5.14. Map of the assessed concession areas.

The computations were carried out with CONOPT [116] as a non-linear programming (NLP) solver. All modeling was performed in the General Algebraic Modeling System (GAMS) modeling language [117], and a GAMS/MATLAB interface was developed to plot the results. The computational time was relatively fast, around 15.1 minutes [14] on an Intel Core i7 3.4 GHz processor with 16 GB RAM, with a α step of 0.01. The same case study was performed in Paper *h*.

By solving the proposed MOO problem with varying weight α, the Pareto frontiers and the knee sets illustrated in Figure 5.15 are obtained. The edges of the knee sets are defined as the points with minimum d_1 (Manhattan) and d_∞ (Chebyshev) distances to the utopia solutions (z_{U2}, z_{U1}). Such distances were normalized as indicated in Equation (5.5.1).

In addition to the Pareto frontiers and the knee sets, the OL solutions (regulatory framework recently implemented in Brazil) are also illustrated in Figure 5.15. They were obtained by setting the compensations $n(2022) = 100.0\%$, $n(2023) = 95.9\%$, $n(2024) = 91.9\%$, $n(2025) = 87.8\%$, $n(2026) = 83.8\%$, $n(2027) = 79.7\%$, $n(2028) = 75.7\%$, $n(2029) = 73\%$, $n(2030) = 73\%$, as stipulated by law, and by calculating the tariffs so that $EVA(t) = 0, \forall\, t \in \{t_0, \dots, t_1\}$ since ANEEL applies a similar procedure in

[14] Required computational time to solve the MOO problem and plot the results in MATLAB. It includes all α values and all concession areas.

practice. Therefore, the OL solutions are used as a baseline to evaluate the performance of the proposed model.

As verified in Figure 5.15, $PEI[EWA(t), CGWP(t)]$ and $PEI[T(t)]$ are conflicting objectives. This is because while DG can create socioeconomic welfare and lead to environmental benefits (advantageous from the perspective of $PEI[EWA(t), GWP(t)]$), it can also imply tariff raises (detrimental from the perspective of $PEI[T(t)]$). Moreover, results demonstrate that the OL solutions are non-optimal or dominated since they are not located on the optimal Pareto frontiers. The PEI results of the OL solutions and proposed model are indicated in Table 5.6, assuming the Euclidian knee points for the latter. Inside brackets, the percentage change is represented, where "B." denotes a benefit (the optimization improved the PEI compared to the OL) and "D." denotes a deterioration (the optimization deteriorated the PEI compared to the OL). Benefits averaging 33% were achieved in terms of electricity tariff affordability (simple average of the percentage changes indicated in column $PEI[T(t)]$), with small deteriorations of around 8% in terms of socioeconomic welfare and global warming potential (simple average of the percentage changes indicated in column $PEI[EWA(t), GWP(t)]$).

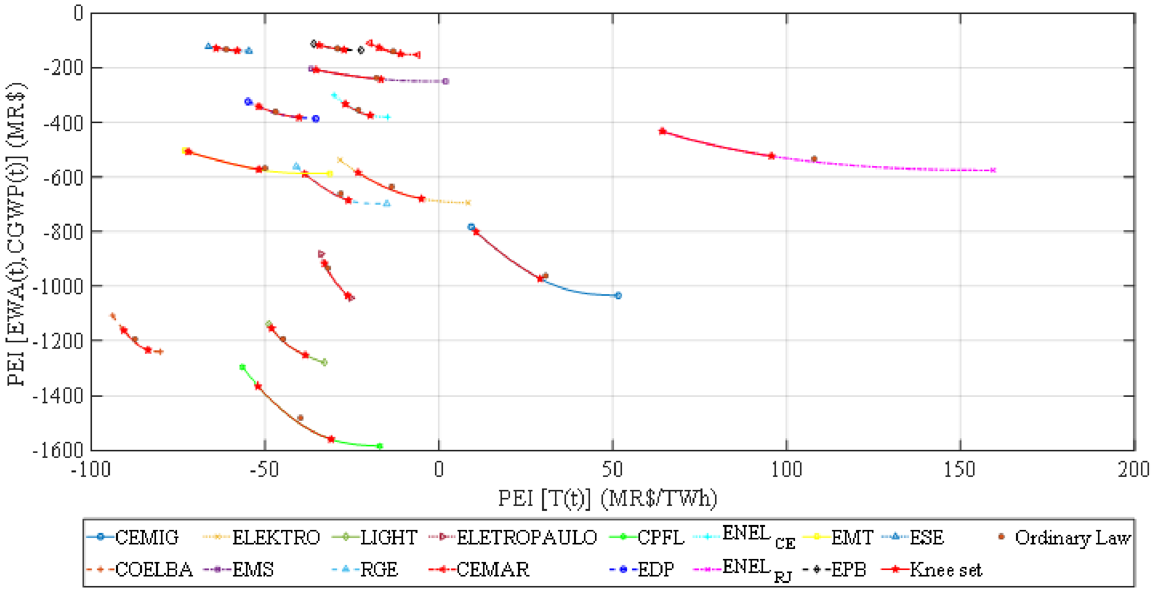

Figure 5.15. Pareto frontiers and OL solutions.

TABLE 5.6. PEI RESULTS (EUCLIDIAN KNEE POINTS).

	$PEI[T(t)]$ (MR$/TWh)		$PEI[EWA(t), GWP(t)]$ (MR$)	
	OL (baseline scenario)	Proposed model	OL (baseline scenario)	Proposed model
CEMIG	30.7	9.3 (69.7% B.)	−962.7	−783.7 (18.6% D.)
COELBA	−87.5	−88.3 (0.9% B.)	−1194.1	−1196.8 (0.2% B.)
ELEKTRO	−13.6	−28.5 (109.6% B.)	−635.7	−537.9 (15.4% D.)
EMS	−18.0	−36.8 (104.4% B.)	−236.6	−204.0 (13.8% D.)
LIGHT	−44.9	−48.2 (7.3% B.)	−1193.5	−1154.9 (3.2% D.)

RGE	−28.3	−39.5 (39.6% B.)	−661.5	−579.8 (12.4% D.)
ELETROPAULO	−32.0	−32.3 (0.9% B.)	−934.0	−935.7 (0.2% B.)
CEMAR	−13.2	−16.1 (22.0% B.)	−140.1	−132.0 (5.8% D.)
CPFL	−39.8	−48.8 (22.6% B.)	−1480.4	−1409.2 (4.8% D.)
EDP	−47.0	−48.9 (4.0% B.)	−360.3	−357.2 (0.9% D.)
$ENEL_{CE}$	−23.2	−25.3 (9.1% B.)	−353.6	−346.7 (2.0% D.)
$ENEL_{RJ}$	107.9	64.2 (40.5% B.)	−533.6	−433.0 (18.9% D.)
EMT	−50.1	−70.1 (39.9% B.)	−567.8	−515.8 (9.2% D.)
EPB	−29.3	−34.4 (17.4% B.)	−128.9	−117.8 (8.6% D.)
ESE	−61.2	−62.9 (2.8% B.)	−132.1	−130.4 (1.3% D.)

"B." denotes a benefit, whereas "D." denotes a deterioration.

The optimal compensations for the electricity injected into the grid over time are illustrated in Figure 5.16 (Euclidian knee points). In general, the model indicates that either the compensation should be maintained at 100% or decreased in the medium term, *i.e.*, short-term decreases in compensation are not suggested.

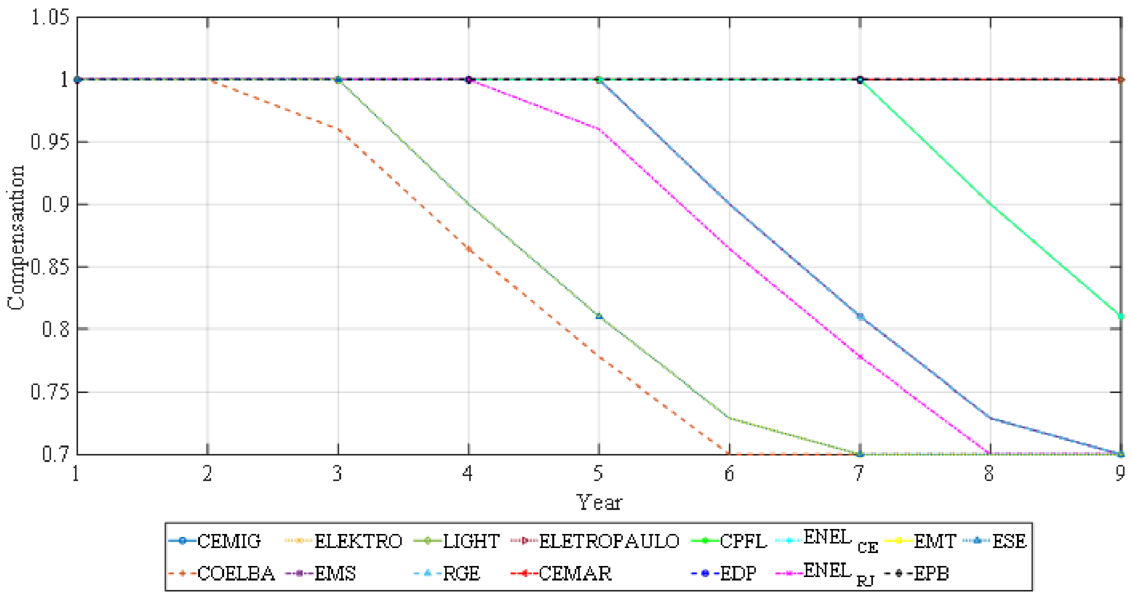

Figure 5.16. Optimal compensations (Euclidian knee points).

The optimal regulated electricity tariffs are illustrated in Figure 5.17 (Euclidian knee points). In this case, the shapes vary widely. For concession areas where the compensation decreases (*e.g.*, $ENEL_{RJ}$), there is generally a tariff increase in the short and medium term followed by a tariff decrease in the long term. This is because DG is not strongly detrimental to the DISCO for a compensation of 0.7, which takes place in the long term. Thus, it is possible to decrease the tariff without leading to the company's bankruptcy. On the other hand, for companies where the compensation does not decrease (*e.g.*, LIGHT), the tariff might increase continuously throughout the simulation period to avoid company bankruptcy.

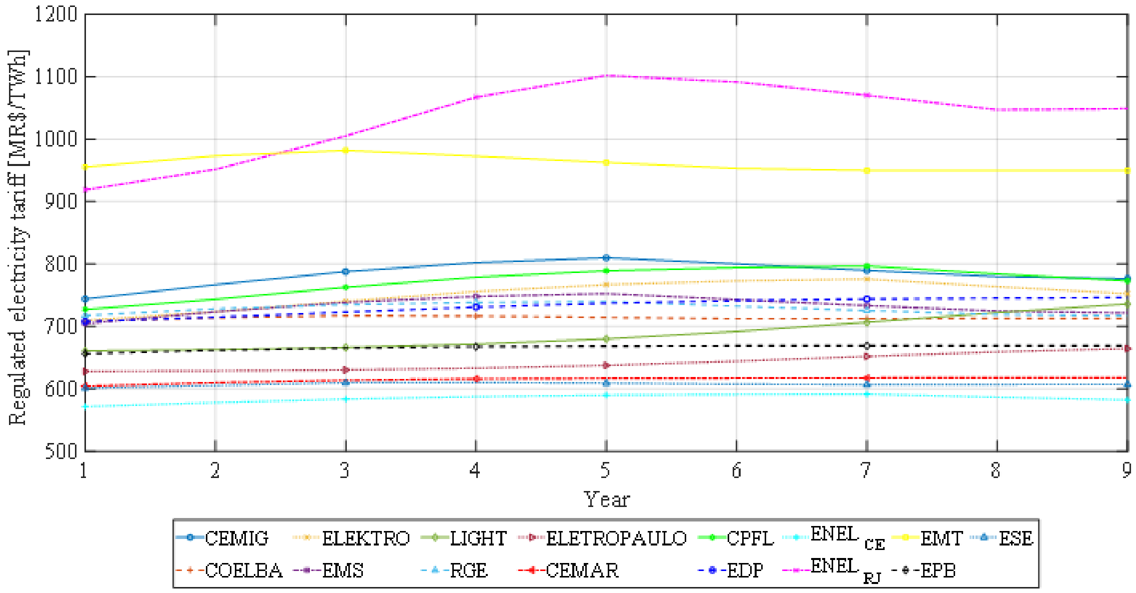

Figure 5.17. Optimal regulated electricity tariffs (Euclidian knee points).

It is noteworthy that while the results were presented assuming the Euclidian knee points, which is a typical approach in MOO problems, any points located in the knee sets can be considered. Thus, human experience and expertise are important in this sense for selecting specific points in the knee sets. For instance, the regulatory agency might perceive that the compensations of the Euclidian knee points are impractical and seek a more "balanced" solution. That being said, decision-making processes conducted by the regulatory agency should always be unbiased and transparent.

5.4 Co-existence between conventional markets and CBMs

In this section, CBMs are introduced into the MOO problem presented in Section 5.3. Moreover, energy poverty issues are addressed in more detail through a new index.

5.4.1 Modeling assumptions

The implementation of CBMs is currently very limited. Hence, several associated uncertainties (*e.g.*, legal uncertainties) exist, particularly in Brazil, where electricity markets are deferred compared to developed countries. For such reason, it is essential to describe the modeling assumptions clearly, as outlined below:

- It is assumed that prosumers choose the most profitable option between the injection of electricity surplus into the grid or local commercialization. If both options are equally profitable, local commercialization is assumed to take place since the evaluated communities are groups of members that share common interests and cooperate with each other [14];

- CBMs tend to become more advantageous over time due to the increase in the available amount of electricity to be commercialized and the decrease in prices. Therefore, there are generally no incentives to return to conventional markets. For such reason, it is considered that consumers do not move from the CBMs to conventional markets;

• It is assumed as a public policy that low-income consumers have priority to purchase electricity in the local market, as it is intended to assess potential mitigations in energy poverty induced by CBMs;

• Following recent trends in Brazil, which implemented the remote DG option [118], it is assumed that the only geographic constraint is to be within the same concession area.

It is emphasized that the considerations mentioned above are easily adaptable in the model, for investigation in future scenarios.

5.4.2 Prosumer model

The prosumer surplus, which is represented separately from the consumer surplus, is given by Equation (5.6):

$$ECA_p(t) = a_p E_p(t) - \frac{b_p}{2} {E_p}^2(t) - T(t)\{E_{pr}(t) - (1-l)E_g(t)[x(t)n_r(t) + y(t)n_l(t)]\} \quad (5.6)$$

where: $ECA_p(t)$ is the prosumer surplus and t is the time. a and b are parameters associated with the willingness to consume electricity and the degree of satisfaction with the consumed electricity, respectively. $E_p(t)$ is the electricity consumption (grid and DG) and $E_{pr}(t)$ is the electricity consumption from the grid. $T(t)$ is the regulated electricity tariff. $E_g(t)$ is the generated electricity from DG. l is the self-consumption ratio. $x(t)$ and $y(t)$ are binary variables that indicate injection of electricity into the grid and local commercialization, respectively. $(1-l)x(t)E_g(t)$ is the generated electricity from DG injected into the grid, whereas $(1-l)y(t)E_g(t)$ is the generated electricity from DG commercialized locally, *i.e.*, the electricity traded in the CBM. $n_r(t)$ and $n_l(t)$ are the compensations for the electricity injected into the grid and electricity commercialized locally, respectively. $T(t)\{E_{pr}(t) - (1-l)E_g(t)[x(t)n_r(t) + y(t)n_l(t)]\}$ quantifies the revenue paid to the DISCO and earnings with the transaction of electricity from DG (economic issues).

From the problem definition, Equation (5.7) is obtained:

$$E_p(t) = E_{pr}(t) + lE_g(t) \quad (5.7)$$

where: $lE_g(t)$ is the DG self-consumption.

In this section, DR issues are modeled more accurately based on the composed average electricity tariff. For prosumers, Equation (5.8) is applied:

$$E_p(t) = \frac{a_p - \frac{T(t)E_{pr}(t) + T(t)[x(t)n_r(t) + y(t)n_l(t)]lE_g(t)}{E_p(t)}}{b_p} \quad (5.8)$$

where: $\{T(t)E_{pr}(t) + T(t)[x(t)n_r(t) + y(t)n_l(t)]lE_g(t)\}/E_p(t)$ is the composed average electricity tariff from the perspective of prosumers. $T(t)$ is the tariff associated with the electricity consumed from the grid $E_{pr}(t)$, while $T(t)[x(t)n_r(t) + y(t)n_l(t)]$ is the tariff associated with the electricity consumed from the DG system $lE_g(t)$. The latter represents an opportunity cost since prosumers can transact the electricity from DG at a price $T(t)[x(t)n_r(t) + y(t)n_l(t)]$.

5.4.3 Consumer model

The consumer surplus is modeled by Equation (5.9):

$$ECA_c(t) = a_c E_c(t) - \frac{b_c}{2} E_c{}^2(t) - T(t)\left[E_r(t) + n_l(t)(1-l)y(t)E_g(t)\right] \tag{5.9}$$

where: $ECA_c(t)$ is the consumer surplus. a_c and b_c are analogous to Equation (5.6). $T(t)\left[E_r(t) + n_l(t)(1-l)y(t)E_g(t)\right]$ quantifies the revenue paid to the DISCO and expenses associated with purchasing electricity locally. $E_c(t)$ is the electricity consumption (grid and DG), $E_r(t)$ is the electricity consumption from the grid, and $(1-l)y(t)E_g(t)$ is the electricity commercialized locally in the CBM. Hence, Equation (5.10) is obtained:

$$E_c(t) = E_r(t) + (1-l)y(t)E_g(t) \tag{5.10}$$

For consumers, Equation (5.11) is applied to model DR issues:

$$E_c(t) = \frac{a_c - \frac{T(t)\left[E_r(t) + n_l(t)(1-l)y(t)E_g(t)\right]}{E_c(t)}}{b_c} \tag{5.11}$$

where: $T(t)\left[E_r(t) + (1-l)y(t)n_l(t)E_g(t)\right]/E_c(t)$ is the composed average electricity tariff from the perspective of conventional consumers. $T(t)$ is the tariff associated with the electricity consumed from the grid $E_r(t)$, while $T(t)n_l(t)$ is the tariff associated with the electricity commercialized locally $(1-l)y(t)E_g(t)$.

5.4.4 Regulated DISCO model and socioeconomic welfare

The DISCO's financial structure is assumed to be similar to that of Chapter 4, but with changes in the company's revenue. Thus, Equation (5.12) is obtained:

$$EVA(t) = (1 - t_t) \cdot \left\{ \begin{array}{c} T(t)\left\{E(t) - E_g(t)\{l + (1-l)[x(t)n_r(t) + y(t)]\}\right\} - \\ \left\{ \begin{array}{c} eE(t) - e'E_G(t) + \dfrac{f\left[\frac{E_G(t)}{E(t)}\right]^2 + g\frac{E_G(t)}{E(t)} + pE^2(t)}{B(t)} + \\ \mu T(t)\left\{E(t) - E_g(t)\{l + (1-l)[x(t)n_r(t) + y(t)]\}\right\} + B(t)k \end{array} \right\} \end{array} \right\} \tag{5.12}$$

It is noteworthy that EVA is independent of the electricity price in the CBM ($n_l(t)$). However, it is influenced by whether or not such a market takes place ($y(t)$).

From the problem definition, Equation (5.13) is obtained:

$$E(t) = E_c(t) + E_p(t) \tag{5.13}$$

The optimal grid investment is the same as Equation (4.13). In turn, socioeconomic welfare is given by the sum of the surpluses of all market agents, as presented in Equation (5.14):

$$EWA(t) = ECA_p(t) + ECA_c(t) + EVA(t) \tag{5.14}$$

5.4.5 Energy poverty index and proposed MOO problem

There are three dimensions of energy poverty: physical access, appliance ownership, and electricity affordability [119]. This thesis focuses on the latter dimension due to the economic characteristics of the TAROT model. Although Section 5.3 proposed an index to evaluate electricity affordability ($PEI[T(t)]$), it did not account for the possibility of local commercialization. Therefore, a new index is proposed here to evaluate electricity affordability properly in the context of CBMs.

Previous research on energy poverty has applied the metric "energy expenses divided by total expenses" to evaluate one's level of energy deprivation [119]. Hence, a similar concept is assumed here. However, wages are considered instead of total expenses due to the data available in Brazil. This assumption is appropriate since people in poverty are typically unable to save money. Thus, wages are somewhat similar to the total expenses.

In the context of the proposed model, the electricity expenses divided by the wages is given by Equation (5.15):

$$EEP(t) = \frac{T(t)\left[E_r(t) + n_l(t)(1-l)y(t)E_g(t)\right]}{E_c(t)} \frac{\sum_{r=0}^{r_1} EF(r)}{\sum_{r=0}^{r_1} W(r)} \tag{5.15}$$

where: $EEP(t)$ is the electricity expenses in percentage. $T(t)\left[E_r(t) + (1-h)y(t)n_l(t)E_g(t)\right]/E_c(t)$ is the composed average electricity tariff from the perspective of conventional consumers [15]. r denotes percentile (the idea is to evaluate the group of consumers in energy poverty conditions, which is situated in the lower percentiles, *i.e.*, $r \in \{0, \dots, r_1\}$). $EF(r)$ and $W(r)$ are the electricity consumption and wages per family of conventional consumers, respectively.

The PEI associated with energy poverty is defined as Equation (5.16):

$$PEI[EEP(t)] = \frac{1}{t_1 - t_0} \sum_{t_0}^{t_1} EEP(t) \tag{5.16}$$

[15] Only conventional consumers are assumed since prosumers are generally not in energy poverty conditions.

where: t_0 and t_1 are the initial and final simulation years, respectively.

The proposed MOO problem aims to maximize socioeconomic welfare and minimize the GWP and energy poverty index, as presented in Equation (5.17):

Objective function:

$$\min_{T(t),\, n_r(t),\ \forall t\in\{t_0,\dots,t_1\}} \left\{\frac{\alpha}{z_{N1}-z_{U1}} PEI[EWA(t), CGWP(t)] + \frac{1-\alpha}{z_{N2}-z_{U2}} PEI[EEP(t)]\right\} \tag{5.17.1}$$

Subject to:

Equations (4.13), (4.16), (4.17), (4.18), (5.6), (5.7), (5.8), (5.9), (5.10), (5.11), (5.12), (5.13), (5.14), and (5.15) $\quad \forall\, t \in \{t_0, \dots, t_1\}$

Equations (5.2) and (5.16)

$$EVA(t) \geq 0 \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.2}$$

$$x(t) + y(t) = 1 \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.3}$$

$$n_l(t) \geq n_r(t) - M[1 - y(t)] \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.4}$$

$$n_l(t) < n_r(t) + M[1 - x(t)] \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.5}$$

$$K_{Tl} \leq T(t) \leq K_{Tu} \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.6}$$

$$K_{n_r l} \leq n_r(t) \leq K_{n_r u} \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.7}$$

$$K_{n_l l} \leq n_l(t) \leq K_{n_l u} \qquad \forall\, t \in \{t_0, \dots, t_1\} \tag{5.17.8}$$

$$\chi_{Tl} \leq \frac{T(t)}{T(t-1)} \leq \chi_{Tu} \qquad \forall\, t \in \{t_0 + 1, \dots, t_1\} \tag{5.17.9}$$

$$\chi_{n_r l} \leq \frac{n_r(t)}{n_r(t-1)} \leq \chi_{n_r u} \qquad \forall\, t \in \{t_0 + 1, \dots, t_1\} \tag{5.17.10}$$

$$\chi_{n_l l} \leq \frac{n_l(t)}{n_l(t-1)} \leq \chi_{n_l u} \qquad \forall\, t \in \{t_0+1, \dots, t_1\} \tag{5.17.11}$$

$$y(t) - y(t-1) \geq 0 \qquad \forall\, t \in \{t_0+1, \dots, t_1\} \tag{5.17.12}$$

where: α and $(1-\alpha)$ are the weights assigned to functions 1 ($PEI[EWA(t), CGWP(t)]$) and 2 ($PEI[EEP(t)]$), respectively. z_{N1} and z_{N2} are the nadir points of functions 1 and 2, respectively. z_{U1} and z_{U2} are the utopia points of functions 1 and 2, respectively. The design variables are the regulated electricity tariff ($T(t)$) and the compensation for the electricity injected into the grid ($n_r(t)$). Equation (4.13) regards the optimal grid investment. Equations (4.16), (4.17), and (4.18) model DG integration over time. Equation (5.6) models the prosumer surplus. Equations (5.7), (5.10), and (5.13) are trivial, as (5.7) and (5.10) assert that the electricity consumed by prosumers and consumers has two components: grid and DG, whereas (5.13) asserts that the overall consumed electricity considers both prosumers and consumers. Equations (5.8) and (5.11) represent DR issues concerning prosumers and consumers, respectively. Equation (5.9) corresponds to the consumer surplus. Equation (5.12) concerns the DISCO surplus. Equation (5.14) quantifies socioeconomic welfare. Equation (5.15) models energy poverty issues. Equation (5.2) is associated with the PEI of socioeconomic welfare and cost of global warming potential, whereas Equation (5.16) is associated with the PEI of energy poverty issues. Equation (5.17.2) is applied to avoid the DISCO bankruptcy. Equation (5.17.3) is applied since prosumers inject their surplus of electricity into the grid or commercialize it locally in the CBM. Equations (5.17.4) and (5.17.5) are applied since prosumers trade their surplus of electricity in the market with higher compensation. These constraints are implemented based on the big M method (M should be a sufficiently big number) since it mimics the role of logical expressions that are difficult to apply directly in mathematical programming and hard to compute. Furthermore, the big M method is computationally efficient due to its linearity. Equations (5.17.6), (5.17.7), and (5.17.8) are applied as lower and upper boundaries for the regulated electricity tariff, compensation for the electricity injected into the grid, and compensation for the electricity commercialized locally in the CBM, respectively. Equations (5.17.9), (5.17.10), and (5.17.11) are applied to avoid abrupt oscillations in the same variables. Equation (5.17.12) is applied to prevent consumers from returning to conventional markets (contractual issues).

It is also important to quantify the benefits of CBMs in mitigating energy poverty, which is done based on Equation (5.18):

$$\Delta PEI[EEP(t)] = \frac{\left[PEI[EEP(t)]\right]_{with\ y(t)=0} - \left[PEI[EEP(t)]\right]_{with\ binary\ y(t)}}{\left[PEI[EEP(t)]\right]_{with\ y(t)=0}} \tag{5.18}$$

where: $\Delta PEI[EEP(t)]$ is the variation in electricity expenses. $[PEI[EEP(t)]]_{with\ binary\ y(t)}$ is the electricity expenses assuming the presence of CBMs. $[PEI[EEP(t)]]_{with\ y(t)=0}$ is the electricity expenses assuming the absence of CBMs (the same solution as $[PEI[EEP(t)]]_{with\ binary\ y(t)}$, but assuming that the surplus of electricity is injected into the grid).

The applied solving process is similar to that presented in Table 5.4.

5.4.6 Case study

The proposed model was applied to the same fifteen Brazilian concession areas analyzed in Section 5.3.1. Regarding the parameters $EF(r)$ and $W(r)$ used to quantify energy poverty issues (Equation (5.15)), data from the Brazilian Institute of Geography and Statistics (IBGE) and the power utility company Eletrobras were used (data per state) [120], [121], [122], [123]. Moreover, the poorest 20% of the population were analyzed due to their critical socioeconomic conditions, *i.e.*, $r \in \{0, \ldots, 20\%\}$.

As boundaries for the variables, it was assumed $0.7 \leq n_r(t) \leq 1.1$ and $0.7 \leq n_l(t) \leq 1.0$. These values are coherent with the Brazilian context and enable a proper evaluation of the model's behavior and performance, as detailed in Paper *i*. Specifically: (*i*) the approved regulatory framework (OL) will set a compensation of about 0.7, (*ii*) there is no reason for $n_l(t)$ to be higher than one since the electricity commercialized locally must be cheaper than the electricity purchased from the DISCO, (*iii*) a maximum $n_r(t)$ of 1.1 makes it possible to analyze whether the regulatory agency should consider increasing the economic benefit of injecting electricity into the grid, thus boosting the DG installed capacity. Concerning the regulated electricity tariff (Equation (5.17.6)), broad boundaries can be assigned without affecting the solution. Additionally, variations of up to ±10% are allowed annually, *i.e.*, $\chi_{Tl} = \chi_{n_r l} = \chi_{n_l l} = 0.9$ and $\chi_{Tu} = \chi_{n_r u} = \chi_{n_l u} = 1.1$.

The computations were carried out with DICOPT [124] as a mixed integer non-linear programming (MINLP) solver. All modeling was performed in the GAMS modeling language [117], and the results were exported to Excel. The computational time was around 2 minutes [16] on an Intel Core i7 3.4 GHz processor with 16 GB RAM, with a α step of 0.05 (a lower step does not change the results significantly). The same case study was performed in Paper *i*.

By solving the proposed MOO problem with varying weight α, the Pareto frontiers illustrated in Figure 5.18 are obtained. $PEI[EWA(t), CGWP(t)]$ and $PEI[EEP(t)]$ are conflicting objectives to some extent since improving one of the objectives tends to deteriorate the other.

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[16] Required computational time to solve the MOO problem. It includes all α values and all concession areas. However, it does not include the process of exporting and plotting the results as this was done manually.

Two factors influence $PEI[EEP(t)]$ in Figure 5.18: (*i*) the composed average electricity tariff from the perspective of conventional consumers, which depends on the price of the electricity purchased from the grid ($T(t)$) and purchased in the local market ($n_l(t)T(t)$), in addition to the available electricity to be purchased in the local market ($(1-l)y(t)E_g(t)$), and (*ii*) the socioeconomic conditions of the low-income population ($EF(r)$ and $W(r)$). Therefore, concession areas where the electricity price is naturally high and where socioeconomic conditions are critical have a higher $PEI[EEP(t)]$, indicating alarming energy poverty concerns. In turn, several factors influence $PEI[EWA(t), CGWP(t)]$. However, the scale of the concession area is very influential, justifying why concession areas with high electricity consumption are located further down the y-axis. Namely, large-scale concession areas are expected to create more socio-economic welfare.

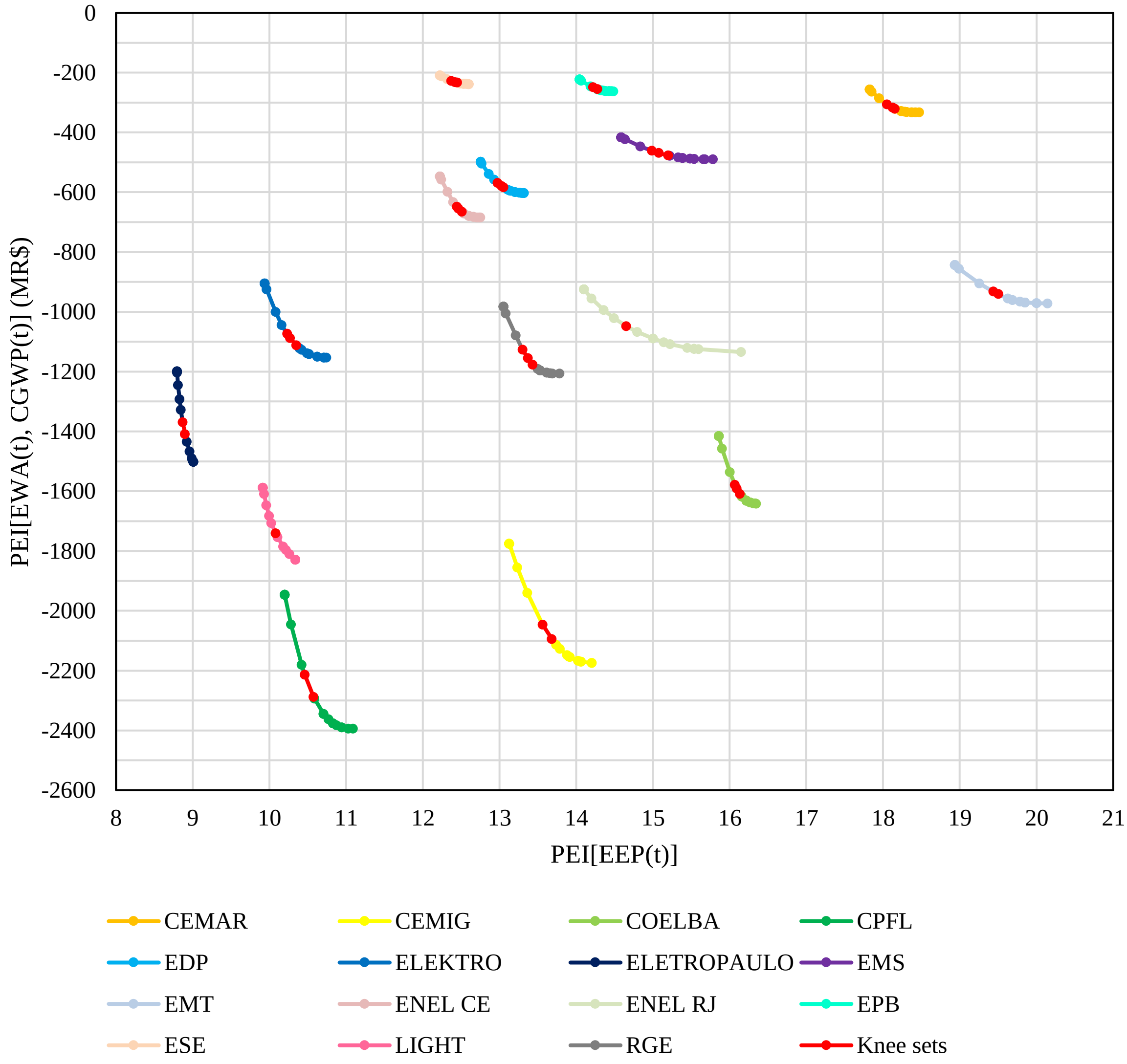

Figure 5.18. Pareto frontiers.

Assuming the Euclidian knee points, the optimal compensations are illustrated in Figure 5.19. Only the highest compensation between $n_l(t)$ (local commercialization) and $n_r(t)$ (injection of electricity into the grid) is illustrated since prosumers are expected to select the most profitable option. The model indicates that setting a higher compensation rate $n_r(t)$ during the early years, and injecting electricity into the grid is beneficial. This strategy ensures a boost in the DG installed capacity and early benefits for prosumers and the environment. However, it tends to harm DISCOs and imply tariff raises. Consequently, the model suggests that $n_r(t)$ should be decreased in the medium term (when the DG sector is already well developed), causing prosumers to trade electricity with conventional consumers in the local market at more affordable prices, thus contributing to energy poverty mitigation.

In some concession areas, the compensation decreases slowly (*e.g.*, ELETROPAULO and LIGHT). Although several factors influence the optimal solution, such concession areas generally present incipient DG integration compared to their potential. Therefore, it is beneficial to maintain a high compensation for a few more years to foster DG integration. Moreover, ELETROPAULO and LIGHT do not exhibit particularly worrying tariff raises. Hence, their high compensation is not alarming from the energy poverty perspective.

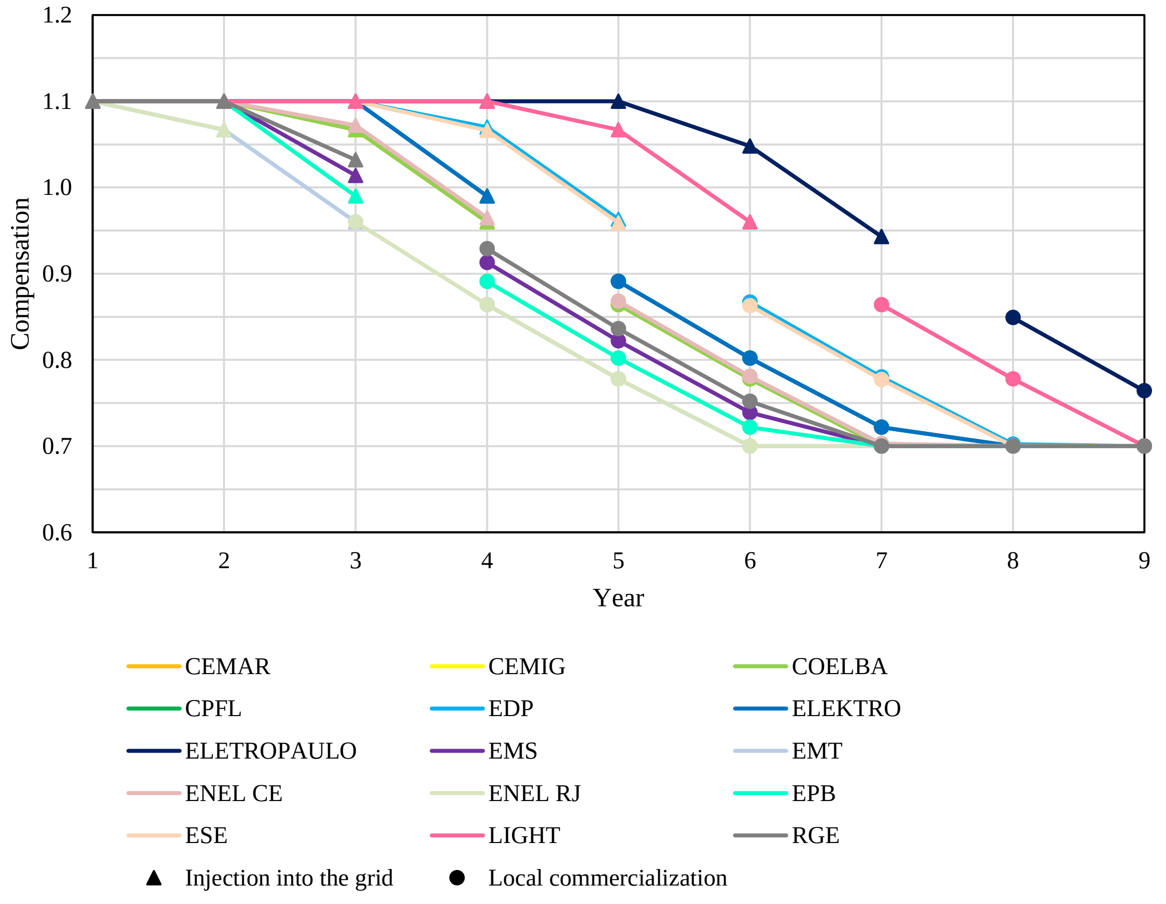

Figure 5.19. Optimal compensations (Euclidian knee points).

Again assuming the Euclidian knee points, the optimal regulated electricity tariffs are illustrated in Figure 5.20. For ease of viewing, the tariffs are represented in p.u., which is calculated by dividing the optimal tariff by the initial tariff provided by the regulatory agency. In general, there is a medium-term increase in the tariffs to keep up with the higher compensation illustrated in Figure 5.19 and the higher DG penetration. This is typically necessary to ensure FEE for the DISCOs and avoid their bankruptcy. However, the tariffs tend to stabilize in the long term since the compensation decreases and the integration of DG starts to flatten. It is also noteworthy that the tariffs are mostly lower than one p.u. during the early years, indicating that the current regulated tariffs are excessive.

ENEL RJ's regulated tariff increases substantially due to its high DG penetration relative to its market size, *i.e.*, high $E_G(t)/E(t)$ ratio. Specifically, ENEL RJ presents a low payback time and payback sensitivity, justifying its notable DG penetration. It should also be noted that ENEL RJ's compensation is the fastest decreasing in Figure 5.19 to prevent additional tariff raises.

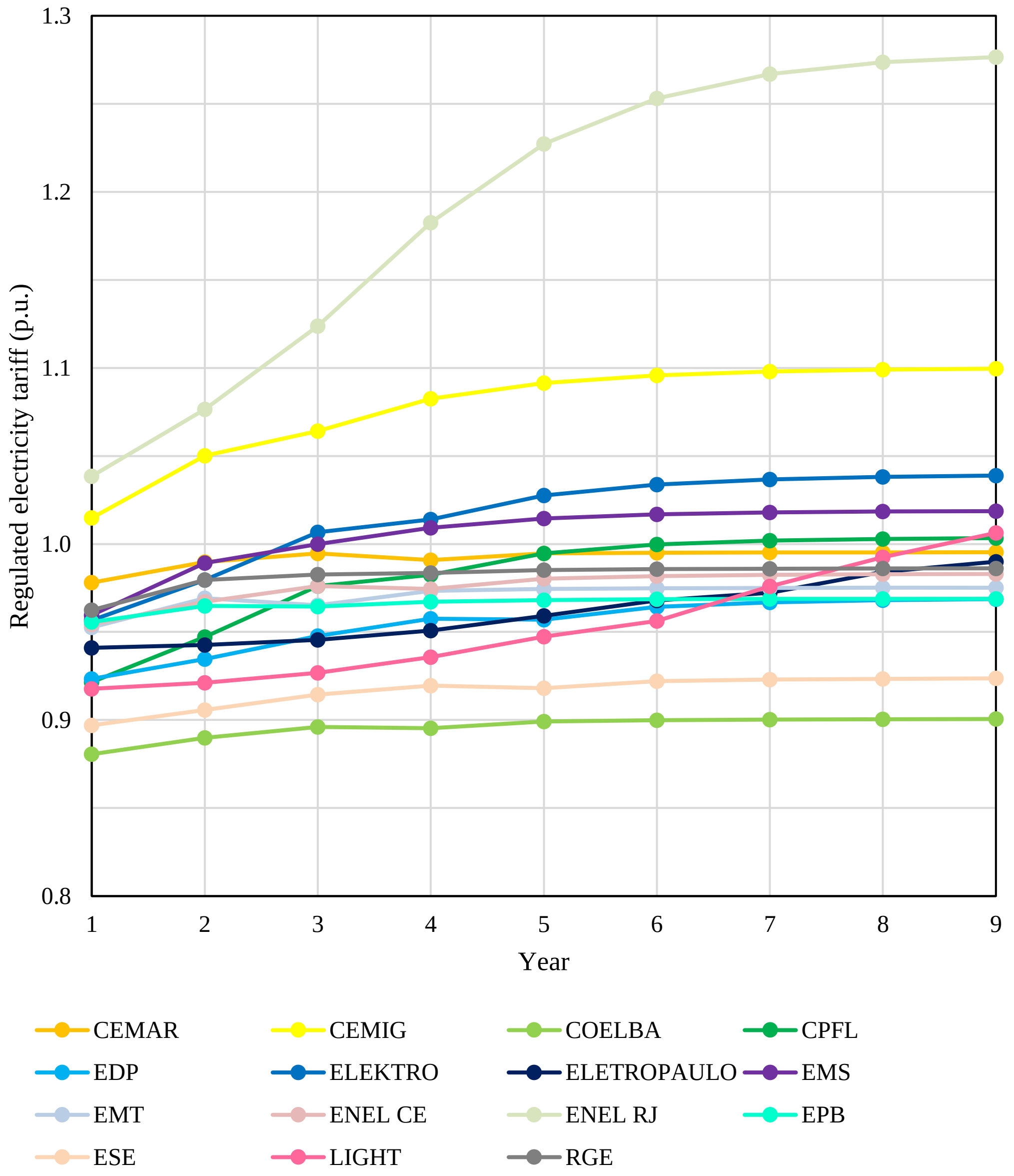

Figure 5.20. Optimal regulated electricity tariffs (Euclidian knee points).

The estimations concerning local commercialization and injection into the grid are illustrated in Figure 5.21. Self-consumption is not represented for ease of viewing, but it should be mentioned that the self-consumption ratio is about 50%, meaning that approximately half of the electricity is sold and the other half is self-consumed. The compensations $n_l(t)$ and $n_r(t)$ dictate whether injection into the grid or local commercialization occurs since prosumers are expected to select the most profitable option. The S-shaped curves are typical of the BDM. Specifically, a large increase in the number of prosumers (or electricity from DG) is expected in the medium term, as there is vast market potential to adopt the technology. However, the curves flatten towards the end of the period, when most potential adopters have already acquired the technology.

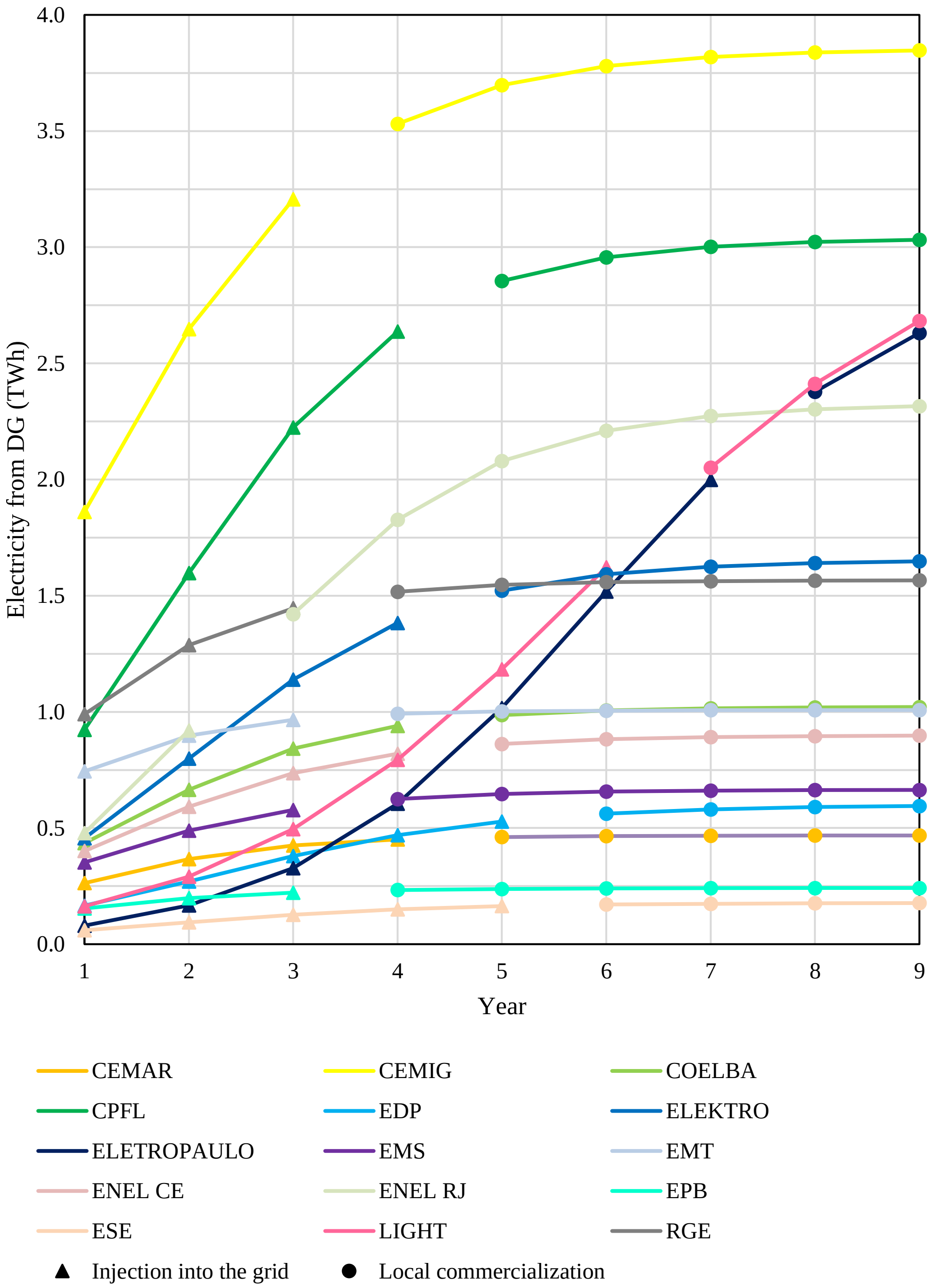

Figure 5.21. Estimations of locally commercialized electricity and electricity injected into the grid from DG.

It is essential to assess the benefits created by CBMs based on Equation (5.18), as one can see in Table 5.7. As demonstrated, CBMs can be significantly beneficial in mitigating energy poverty in Brazil, as on average $\Delta PEI[EEP(t)]$ is equal to 1.9%. However, it is clear that CBMs would not solve the problem by themselves. Specifically, although the electricity price in CBMs can be well below the conventional tariff, the available amount of electricity to be commercialized is limited compared to the whole regulated market. Therefore, additional measures (*e.g.*, subsidies) should be implemented for more notable mitigations in energy poverty.

It is noteworthy that the calculations in Table 5.7 take into account the whole regulated market. The benefits in mitigating energy poverty considering only the CBMs participants (disregarding $E_r(t)$ in Equation (5.15)) are about 13.6%. This result highlights that the available amount of electricity to be commercialized is a limiting factor.

TABLE 5.7. BENEFITS OF CBMS IN MITIGATING ENERGY POVERTY.

	$[PEI[EEP(t)]]_{with\ y(t)=0}$ (%)	$[PEI[EEP(t)]]_{with\ binary\ y(t)}$ (%)	$\Delta PEI[EEP(t)]$ (%)
CEMAR	18.36	18.17	1.00
CEMIG	13.99	13.57	2.98
COELBA	16.23	16.10	0.82
CPFL	10.84	10.58	2.40
EDP	13.19	13.05	1.05
ELEKTRO	10.54	10.28	2.42
ELETROPAULO	8.94	8.91	0.38
EMS	15.53	15.12	2.69
EMT	19.96	19.47	2.45
ENEL CE	12.61	12.45	1.24
ENEL RJ	15.72	14.68	6.59
EPB	14.40	14.25	1.02
ESE	12.54	12.46	0.68
LIGHT	10.20	10.09	1.02
RGE	13.63	13.38	1.82

This chapter achieved objectives (*iii*), (*iv*), and (*v*) and answered RQ3 and RQ4.

5.5 Summary of results and analysis

A holistic approach to analyzing the implications of the OL and seeking optimal regulatory solutions was presented in this chapter. The results demonstrated that:

- The OL will in fact decrease the regulated tariffs, but trade-offs in the form of socioeconomic welfare losses and GWP deteriorations are envisaged. Although decreases in the compensation for the electricity injected into the grid are necessary, the main criticism derived from the research is the fact that the OL was designed empirically, making it sub-optimal as per the results obtained from the MOO approach, in which the OL solution was not located in the Pareto frontiers;

- The Pareto frontiers indicated that regulated tariff affordability is a conflicting aspect relative to socioeconomic welfare and GWP. Moreover, DG tends to be detrimental for the former and beneficial for the latter [17];
- The effects of DG on the regulated market and the implications of the OL significantly depend on the region and concession area;
- Comparing the optimal solution to the OL, benefits averaging 33% were achieved in terms of electricity tariff affordability, with small deteriorations of around 8% in terms of socioeconomic welfare and GWP. These results highlight significant improvement opportunities;
- In the context of conventional markets and CBMs coexistence, conventional markets tend to be beneficial in the short term and CBMs in the medium term. This perspective ensures both a satisfactory share of DG in the market and later commercialization of electricity at more affordable prices, mitigating energy poverty. However, the regulatory agency should responsibly set the compensation for the electricity injected into the grid, taking into account the interests of all market players;
- CBMs can be beneficial in mitigating energy poverty, as the case study indicated a benefit of around 1.9% assuming the entire regulated market or 13.6% considering only the CBMs participants. However, such benefits would only take place if the low-income population could participate in CBMs.

[17] Assuming reasonable DG penetration. For excessive DG penetration, DG tends to be detrimental regarding socioeconomic welfare.

6 BRIDGING THE GAP BETWEEN REGULATORY AND OPERATIONAL ASPECTS

Chapters 3 to 5 presented the TAROT and extensions of the model that do not consider the electrical grid. In turn, this chapter considers an integrated approach where the electrical grid is modeled within the optimization problem. Such an approach is advantageous in the following points:

(*i*) It accurately quantifies energy loss and DG self-consumption, which were highly simplified in Chapters 3 to 5;

(*ii*) It models the locational aspect of DG deployment, which can be used for interdisciplinary assessments (*e.g.*, analyzing whether DG uptake has a detrimental outcome in terms of overvoltage), although this thesis focuses on regulatory issues;

(*iii*) It accounts for the uncertainties associated with DG uptake, thus providing a more comprehensive view of the market (*e.g.*, worst-case scenarios associated with DG deployment). Such a comprehensive view can aid the regulatory agency in implementing better solutions;

(*iv*) It can be used to estimate future grid-reinforcement requirements (*e.g.*, cable reinforcements, deployment of shunt capacitors, and replacement of transformers) to increase the accuracy of the grid investment parameter. However, grid reinforcement approaches were not modeled in this thesis and should be addressed in future work.

As the main drawback of the model proposed in this chapter, one should mention its high intricacy and computational time. For such reason, single-objective optimization is considered and CBMs are disregarded, but once enhanced computational performance is achieved in future work, the inclusion of MOO and CBMs is encouraged.

6.1 Scenario-based, locational, and time-dependent model of DG systems uptake

The model of DG systems uptake is developed from the BDM with significant improvements. The active power generation from DG is modeled by Equations (6.1) and (6.2):

$$P_{dg}(i,t,y) = PMPP(i,y)Irrad(t) \tag{6.1}$$

$$PMPP(i,y) = \left\{(Sizing)[Bin(i,y)]\left[\frac{1}{24}\sum_{t} P_d(i,t,y) - \delta\right]\right\} S_{base} \tag{6.2}$$

where: i, t, and y are the sets of buses, short-term periods (hours), and long-term periods (years), respectively. $PMPP(i,y)$ is the DG system's rated power. $Irrad(t)$ is a typical irradiance curve. $Sizing$ is an adjustable parameter that relates the system's rated power with the mean active power demand $(1/24)\sum_t P_d(i,t,y)$, given that large consumers tend to deploy systems with higher rated power. Such a parameter can be defined based on market research. δ models fixed costs that cannot be offset by DG (*e.g.*, fixed connection costs, which the consumers must pay even if they do not consume electricity). S_{base} is the base apparent power. $Bin(i,y)$ is a binary variable that indicates whether the DG system is deployed. This variable is influenced by historical and economic factors (*e.g.*, the probability of deployment increases with DG profitability). The probability of deployment is calculated through Equation (6.3):

$$Prob(i,y) = e^{-(PBS)[PBT(i,y)]} \frac{(p_B + q_B)e^{-(p_B+q_B)y}\left\{1 + \frac{q_B}{p_B}\left[1 + e^{-(p_B+q_B)y}\right]\right\}}{\left[1 + \frac{q_B}{p_B}e^{-(p_B+q_B)y}\right]^2} \quad (6.3)$$

where: $Prob(i,y)$ is the probability of DG system deployment, whereas PBS is the payback sensitivity parameter. p_B and q_B are the imitation and innovation parameters, while $PBT(i,y)$ is the payback time, which is modeled similarly to Chapter (5), as per (6.4):

$$PBT(i,y) = \frac{PBT_{base}(1 - PBT_{decrease})^y}{\frac{1}{\lambda}\sum_{\Phi=y}^{\lambda}\left\{\{h(i,y) + [1 - h(i,\Phi)]n(\Phi)\}\frac{T(\Phi)}{T_{base}}\right\}} \quad (6.4)$$

where: PBT_{base} is the payback time for the current market conditions (without changes in the decision variables). T_{base} is the current electricity tariff. $PBT_{decrease}$ represents potential decreases in the payback over time due to falling technology costs. λ is an adjustable parameter. $h(i,y)$ is the DG self-consumption. $n(\Phi)$ is the compensation for the electricity from DG injected into the grid and $T(\Phi)$ is the regulated electricity tariff.

Based on Equations (6.3) and (6.4), one can estimate how the regulatory agency's decision-making influences the probability of DG system deployment. Such a probability affects the values of $Bin(i,y)$, as per Equations (6.5) and (6.6), which were implemented through a soft constraint big M method with two binary variables, one that indicates DG system deployment and the other functions as a penalty to prevent multiple DG systems in the same bus:

$$Uniform(i,y) + Bin_{Pen}(i,y) \leq Prob(i,y) + M_1[1 - Bin(i,y)] \quad (6.5)$$

$$Uniform(i,y) + Bin_{Pen}(i,y) \geq Prob(i,y) - M_1 Bin(i,y) \quad (6.6)$$

where: $Uniform(i,y)$ are random numbers from the uniform probability distribution with bounds [0, 1]. M_1 is a sufficiently big number. $Bin_{Pen}(i,y)$ is the penalty binary variable, which is generally equal to zero unless strictly necessary (to prevent multiple DG systems in the same bus). To ensure such a behavior Bin_{Pen} will be penalized in the objective function. In Equations (6.5) and (6.6), when the random number is lower than the probability, implies that $Bin(i,y) = 1$, *i.e.*, a DG system is deployed. In turn, when the random number is greater than the probability, implies that $Bin(i,y) = 0$. It is noteworthy that if the probability of DG system deployment were constant, the number of DG systems would follow the binomial probability distribution. Equations (6.5) and (6.6) are mathematical mechanisms for simulating every bus independently under distinct probabilities of DG system deployment.

It is necessary to model the DG self-consumption $h(i,\Phi)$ applied in Equation (6.4). To do so, Equations (6.7), (6.8), and (6.9) are employed:

$$(Sizing)\left[\frac{1}{24}\sum_{t} P_d(i,t,y) - \delta\right] Irrad(t) = P_d(i,t,y) + x_1(i,t,y) - x_2(i,t,y) \tag{6.7}$$

$$P_d(i,t,y) \leq (Sizing)\left[\frac{1}{24}\sum_{t} P_d(i,t,y) - \delta\right] Irrad(t) + M_2\left[1 - Bin_{Inj1}(i,t,y)\right] \tag{6.8}$$

$$P_d(i,t,y) \geq (Sizing)\left[\frac{1}{24}\sum_{t} P_d(i,t,y) - \delta\right] Irrad(t) - M_2 Bin_{Inj1}(i,t,y) \tag{6.9}$$

where: $Bin_{Inj1}(i,t,y)$ is a binary variable that indicates power injection into the grid. $x_1(i,t,y) - x_2(i,t,y)$ is the power injection into the grid, in case it occurs (both $x_1(i,t,y)$ and $x_2(i,t,y)$ are defined as positive variables). M_2 is a sufficiently big number. It is noteworthy that the BDM estimates the potential of conventional consumers to become prosumers, justifying the usage of $(Sizing)\left[\frac{1}{24}\sum_t P_d(i,t,y) - \delta\right] Irrad(t)$ in Equations (6.7), (6.8), and (6.9) instead of $P_{dg}(i,t,y)$. In other words, conventional consumers are capable of estimating their self-consumption in the case of DG system deployment to make rational decisions (deploying or not DG systems).

Finally, the DG self-consumption is given by Equation (6.10):

$$h(i,y) = 1 - \frac{\sum_t\left\{\left[Bin_{Inj1}(i,t,y)\right]\left[x_1(i,t,y) - x_2(i,t,y)\right]\right\}}{\sum_t\left\{(Sizing)\left[\frac{1}{24}\sum_t P_d(i,t,y) - \delta\right] Irrad(t)\right\}} \tag{6.10}$$

where: the numerator represents the generated electricity from DG injected into the grid and the denominator denotes the total generated electricity from DG.

Naturally, the proposed model depends on the random numbers applied in Equations (6.5) and (6.6). Thus, a scenario-based approach is essential to verify the influence of random number generation (RNG) on the optimal solution.

6.2 The TAROT model

The TAROT applied in this chapter is slightly different from previous ones due to changes in the energy loss modeling and DG self-consumption. The DISCO revenue is given by Equation (6.11):

$$R(y) = T(y)\left\{E(y) - E_{dg}(y)\{h_2(y) + [1 - h_2(y)]n(y)\}\right\} \tag{6.11}$$

where: $R(y)$ is the revenue. $E(y)$ is the electricity consumption, whereas $E_{dg}(y)$ is the electricity generation from DG. $n(y)$ is the compensation for the electricity from DG injected into the grid. $h_2(y)$ is the compounded DG self-consumption. Differently from the BDM, only actual prosumers are considered in $h_2(y)$, given that prosumer candidates do not influence $E_{dg}(y)$. Hence, Equations (6.12), (6.13), and (6.14) are applied:

$$P_{dg}(i,t,y) = P_d(i,t,y) + x_3(i,t,y) - x_4(i,t,y) \tag{6.12}$$

$$P_d(i,t,y) \leq P_{dg}(i,t,y) + M_2\left[1 - Bin_{Inj2}(i,t,y)\right] \tag{6.13}$$

$$P_d(i,t,y) \geq P_{dg}(i,t,y) - M_2 Bin_{Inj2}(i,t,y) \tag{6.14}$$

where: Equations (6.12), (6.13), and (6.14) are analogous to Equations (6.7), (6.8), and (6.9), respectively, but only considering actual prosumers instead of prosumer candidates. $Bin_{Inj2}(i,t,y)$ is a binary variable that indicates power injection into the grid. $x_3(i,t,y) - x_4(i,t,y)$ is the power injection into the grid, in case it occurs. Both $x_3(i,t,y)$ and $x_4(i,t,y)$ are defined as positive variables.

The compounded DG self-consumption is given by Equation (6.15):

$$h_2(y) = 1 - \frac{\sum_i \sum_t \left\{\left[Bin_{Inj2}(i,t,y)\right]\left[x_3(i,t,y) - x_4(i,t,y)\right]\right\}}{\sum_i \sum_t P_{dg}(i,t,y)} \tag{6.15}$$

where: the numerator represents the compounded generated electricity from DG injected into the grid and the denominator denotes the total compounded generated electricity from DG.

EVA is modeled by Equation (6.16):

$$EVA(y) = (1 - t_t)\left\{R(y) - \left[eE(y) - e'E_{dg}(y)\right] - p'L(y) - \mu R(y) - \left[d + \frac{r_W}{1 - t_t}\right]B(y)\right\} \tag{6.16}$$

where: t_t, e, e', p', μ, d, and r_W are parameters associated with the tax fee, operating costs, influence of DG on the operating costs, cost of energy losses, sales tax, grid depreciation, and the weighted average cost of capital, respectively. $L(y)$ represents the energy losses. $B(y)$ is the grid investment.

ECA is given by Equation (6.17):

$$ECA(y) = aE(y) - \frac{b(y)}{2}[E(y)]^2 - R(y) - s\left[E_{dg}(y)\right](1 - s_{decrease})^y \tag{6.17}$$

where: a and b are parameters related to the willingness to consume electricity and the degree of satisfaction with the consumed electricity, respectively. s is a parameter linked to the CAPEX and OPEX of DG systems, while $s_{decrease}$ models potential decreases in technology costs over time.

Finally, EWA is calculated by Equation (6.18):

$$EWA(y) = ECA(y) + EVA(y) \tag{6.18}$$

The relationship between electricity consumption and regulated tariff, *i.e.*, demand response issues, is given by Equation (6.19):

$$E(y) = \frac{a - T(y)}{b(y)} \quad (6.19)$$

6.3 Power flow model

The branch power flow (BPF) model proposed by Farivar *et al.* [125] is applied since it decreases the computational time of the traditional power flow method while maintaining accuracy [126], [127]. Equations (6.20), (6.21), (6.22), (6.23), (6.24), (6.25), and (6.26) are associated with the active power balance, reactive power balance, current limitation, voltage calculation, voltage limitation, apparent power calculation, and energy losses.

$$\sum_{j,\ j>i} \left[P_{ij}(i,j,t,y) - r(i,j)I(i,j,t,y)\right] + P_g(i,t,y) - P_d(i,t,y) + P_{dg}(i,t,y) = \sum_{k,\ k<i} P_{ij}(k,i,t,y) \quad (6.20)$$

$$\sum_{j,\ j>i} \left[Q_{ij}(i,j,t,y) - x(i,j)I(i,j,t,y)\right] + Q_g(i,t,y) - Q_d(i,t,y) = \sum_{k,\ k<i} Q_{ij}(k,i,t,y) \quad (6.21)$$

$$0 \leq I(i,j,t,y) \leq [I_{max}(i,j,y)]^2 \quad (6.22)$$

$$V(j,t,y) = V(i,t,y) - 2\left[r(i,j)P_{ij}(i,j,t,y) + x(i,j)Q_{ij}(i,j,t,y)\right] + \{[r(i,j)]^2 + [x(i,j)]^2\}I(i,j,t,y) \quad (6.23)$$

$${V_{min}}^2 \leq V(i,t,y) \leq {V_{max}}^2 \quad (6.24)$$

$$[I(i,j,t,y)][V(i,t,y)] = \left[P_{ij}(i,j,t,y)\right]^2 + \left[Q_{ij}(i,j,t,y)\right]^2 \quad (6.25)$$

$$L(y) = \sum_i \sum_t \left[P_g(i,t,y) + P_{dg}(i,t,y) - P_d(i,t,y)\right] S_{base} \Psi \vartheta \quad (6.26)$$

where: i, j, and k are the sets of buses. $P_{ij}(i,j,t,y)$ and $Q_{ij}(i,j,t,y)$ are the active and reactive power injected at the head of branch (i,j), respectively. $r(i,j)$ and $x(i,j)$ are the resistance and reactance of branch (i,j). $P_g(i,t,y)$ and $Q_g(i,t,y)$ are the active and reactive power generation from centralized sources at bus i. $P_d(i,t,y)$ and $Q_d(i,t,y)$ are the active and reactive power demand at bus i. $P_{dg}(i,t,y)$ is the active power generation from DG at bus i. $I(i,j,t,y)$ is the squared current in branch (i,j), whereas $V(i,t,y)$ is the squared voltage at bus i. $I_{max}(i,j,t,y)$, V_{min}, and V_{max} are known limits. Ψ is the number of days per year. ϑ is a conversion factor in kWh/TWh, given that the TAROT is typically applied in TWh.

Equation (6.25) is a nonconvex equality that defines the branch flow at the head bus of each branch. According to Bitencourt *et al.* [126], [127] and Wei *et al.* [128], the problem is more computationally tractable when Equation (6.25) is linearized. From the polyhedral global approximation, Equation (6.25) can be decomposed into Equations (6.27) to (6.44) (see Bitencourt *et al.* [127] for the mathematical proof):

$$\xi_1(i,j,0,t,y) \geq 2P_{ij}(i,j,t,y) \quad (6.27)$$

$$\xi_1(i,j,0,t,y) \geq -2P_{ij}(i,j,t,y) \quad (6.28)$$

$$\eta_1(i,j,0,t,y) \geq 2Q_{ij}(i,j,t,y) \tag{6.29}$$

$$\eta_1(i,j,0,t,y) \geq -2Q_{ij}(i,j,t,y) \tag{6.30}$$

$$\xi_1(i,j,\varphi,t,y) = cos\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_1(i,j,\varphi-1,t,y) + sin\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_1(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.31}$$

$$\eta_1(i,j,\varphi,t,y) \geq -sin\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_1(i,j,\varphi-1,t,y) + cos\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_1(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.32}$$

$$\eta_1(i,j,\varphi,t,y) \geq sin\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_1(i,j,\varphi-1,t,y) - cos\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_1(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.33}$$

$$\xi_1(i,j,\chi,t,y) \leq W(i,j,t,y) \tag{6.34}$$

$$\eta_1(i,j,\chi,t,y) \leq tan\left(\frac{\pi}{2^{\chi+1}}\right)\xi_1(i,j,\chi,t,y) \tag{6.35}$$

$$\xi_2(i,j,0,t,y) \geq W(i,j,t,y) \tag{6.36}$$

$$\xi_2(i,j,0,t,y) \geq -W(i,j,t,y) \tag{6.37}$$

$$\eta_2(i,j,0,t,y) \geq I(i,j,t,y) - V(i,t,y) \tag{6.38}$$

$$\eta_2(i,j,0,t,y) \geq -[I(i,j,t,y) - V(i,t,y)] \tag{6.39}$$

$$\xi_2(i,j,\varphi,t,y) = cos\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_2(i,j,\varphi-1,t,y) + sin\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_2(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.40}$$

$$\eta_2(i,j,\varphi,t,y) \geq -sin\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_2(i,j,\varphi-1,t,y) + cos\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_2(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.41}$$

$$\eta_2(i,j,\varphi,t,y) \geq sin\left(\frac{\pi}{2^{\varphi+1}}\right)\xi_2(i,j,\varphi-1,t,y) - cos\left(\frac{\pi}{2^{\varphi+1}}\right)\eta_2(i,j,\varphi-1,t,y) \qquad \varphi = 1,\dots,\chi \tag{6.42}$$

$$\xi_2(i,j,\chi,t,y) \leq I(i,j,t,y) + V(i,t,y) \tag{6.43}$$

$$\eta_2(i,j,\chi,t,y) \leq tan\left(\frac{\pi}{2^{\chi+1}}\right)\xi_2(i,j,\chi,t,y) \tag{6.44}$$

where: $\xi_1(i,j,\varphi,t,y)$, $\eta_1(i,j,\varphi,t,y)$, $\xi_2(i,j,\varphi,t,y)$, $\eta_2(i,j,\varphi,t,y)$, and $W(i,j,t,y)$ are auxiliary variables, whereas $\varphi = 1,\dots,\chi$ is an auxiliary set. χ is used to adjust the approximation accuracy.

6.4 Integration between long-term and short-term variables

The relationship between energy and power is given by Equations (6.45) and (6.46):

$$E(y) = \sum_i \sum_t [P_d(i,t,y)]\, S_{base} \Psi \vartheta \tag{6.45}$$

$$E_{dg}(y) = \sum_i \sum_t [P_{dg}(i,t,y)]\, S_{base} \Psi \vartheta \tag{6.46}$$

Boundary conditions are required for the active and reactive power demand, as modeled in Equations (6.47) and (6.48):

$$P_d(i,t,y) = [Load_{Curve}(t)][Bus_{Factor}(i)][P_{dMax}(y)] \tag{6.47}$$

$$Q_d(i,t,y) = P_d(i,t,y)\left\{tan\{arccos[p_f(i)]\}\right\} \tag{6.48}$$

where: $Load_{Curve}(t)$ is a characteristic load curve. $Bus_{Factor}(i)$ models the proportion of active power demand between the buses. $P_{dMax}(y)$ is the maximum active power demand of a bus. $p_f(i)$ is the power factor of the buses. If more information is available (*e.g.*, different load curves for each bus), it can be easily incorporated into the model.

6.5 Optimization problem

Environmental aspects are modeled by Equation (6.49):

$$CGWP(y) = (SCC)\{A_{dg}E_{dg}(y) + [A_c(y)][E(y) + L(y) - E_{dg}(y)]\} \tag{6.49}$$

where: $CGWP(y)$ is the cost associated with global warming potential. SCC is a typical social cost of carbon. A_{dg} and $A_c(t)$ are the life cycle emissions of electricity from DG and centralized sources, respectively, obtained from a LCA. $[E(y) + L(y) - E_{dg}(y)]$ represents the generated electricity from centralized sources.

Similar to Chapter 5, socioeconomic and environmental aspects are combined into a single objective for simplicity, as described in Equation (6.50):

$$PEI[EWA(y), CGWP(y)] = EWA(y_0) - \frac{1}{y_1 - y_0}\int_{y_0}^{y_1} EWA(y)dy - CGWP(y_0) + \frac{1}{y_1 - y_0}\int_{y_0}^{y_1} CGWP(y)dy \tag{6.50}$$

An iterative scenario-based bi-level problem is proposed here. The bi-level aspect is due to the separation of the model into two sub-problems: (*i*) regulatory agency's decision-making and (*ii*) optimal power flow. This approach ensures easier convergence and enhanced computational performance compared to a two-stage optimization approach. Sub-problem (*i*) is addressed as the upper-level problem, as it contains the main optimization function (socioeconomic welfare and environmental aspects). In turn, sub-problem (*ii*) is addressed as the lower-level problem since the regulatory agency should account for energy losses to make optimal decisions. It is noteworthy, however, that sub-problems (*i*) and (*ii*) are mutually dependent, thus, an iterative method is conceived. Moreover, due to Equations (6.5) and (6.6), the model's solution depends on the scenario. The proposed algorithm is illustrated in Figure 6.1, with its inner and outer convergence loops. The initial values for the variables are set by replacing the variables with the initial market conditions and applying the equations presented herein (*e.g.*, assuming the parameter PBT_{base} instead of the variable $PBT(i,y)$ in Equation (1.*c*) for setting the initial value of $Prob(i,y)$). This heuristic method is envisaged since it favors convergence.

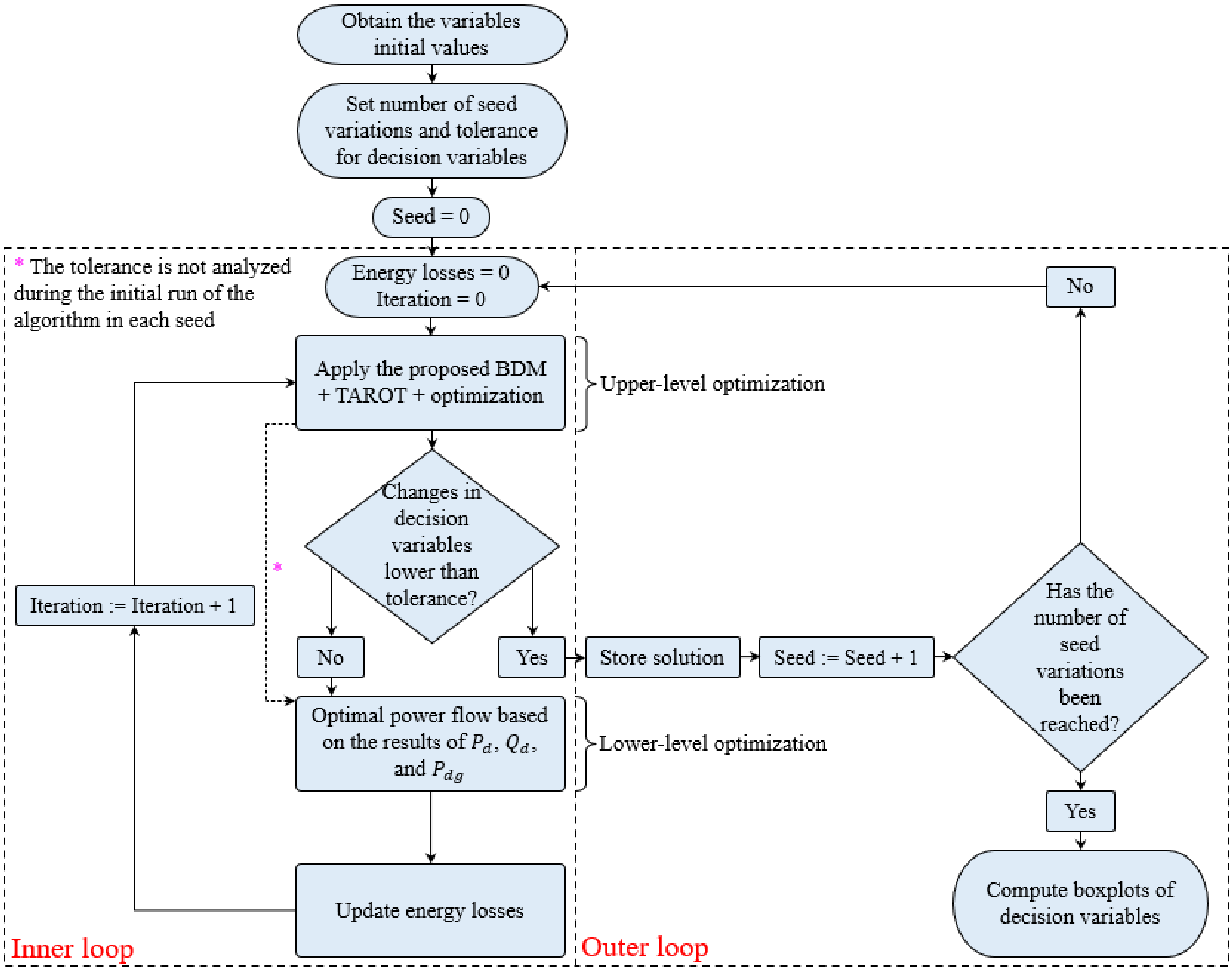

Figure 6.1. Proposed algorithm for solving the iterative scenario-based bi-level problem.

Mathematically, the upper-level sub-problem is defined as follows:

Objective function:

$$\min_{T(y),n(y),\forall y\in\{y_0,\dots,y_1\}} \left\{ PEI[EWA(y), CGWP(y)] + \beta \sum_{i} \sum_{y} Bin_{Pen}(i,y) \right\} \qquad (6.51.1)$$

Subject to:

Equations:

(6.1), (6.7), (6.8), (6.9), (6.12), (6.13), (6.14), (6.47), $\forall\ (i,t,y)$

and (6.48),

Equations: $\forall\ (i,y)$

(6.2), (6.3), (6.4), (6.5), (6.6), and (6.10),

Equations:

(6.11), (6.15), (6.16), (6.17), (6.18), (6.19), (6.45), $\forall\, y$

(6.46), and (6.49),

Equation:

(6.50)

Lower-level constraint:

$$L_{Upper_{Iteration(w)}}(y) = L_{Lower_{Iteration(w-1)}}(y), \qquad \forall\, y \qquad (6.51.2)$$

$$EVA(y) \geq 0, \qquad \forall\, y \qquad (6.51.3)$$

$$K_{Tl} \leq T(y) \leq K_{Tu}, \qquad \forall\, y \qquad (6.51.4)$$

$$K_{nl} \leq n(y) \leq K_{nu}, \qquad \forall\, y \qquad (6.51.5)$$

$$ϟ_{Tl} \leq \frac{T(y)}{T(y-1)} \leq ϟ_{Tu}, \qquad \forall\, y \qquad (6.51.6)$$

$$ϟ_{nl} \leq \frac{n(y)}{n(y-1)} \leq ϟ_{nu}, \qquad \forall\, y \qquad (6.51.7)$$

where: the decision variables are $T(y)$ and $n(y)$, *i.e.*, the regulated electricity tariff and the compensation for the electricity from DG injected into the grid. The parameter β is the weight assigned to the penalization $Bin_{Pen}(i, y)$, as previously detailed in Equations (6.5) and (6.6). Equation (6.51.2) establishes that the energy losses in the upper-level sub-problem in iteration w are equal to the energy losses in the lower-level sub-problem in iteration $w-1$. The first time the upper-level sub-problem is executed, energy losses are addressed as null. Equation (6.51.3) prevents the bankruptcy of DISCOs, whereas Equations (6.51.4), (6.51.5), (6.51.6), and (6.51.7) are applied to limit the decision variables and their variations.

In turn, the lower-level sub-problem is defined as follows:

Objective function:

$$min\left\{\sum_{y} L(y)\right\} \tag{6.52.1}$$

Subject to:

Equations:
(6.27), (6.28), (6.29), (6.30), (6.31), (6.32), (6.33), (6.34), (6.35), (6.36), (6.37), (6.38), (6.39), (6.40), (6.41), (6.42), (6.43), and (6.44), $\forall\ (i, j, \varphi, t, y)$

Equations:
(6.22) and (6.23), $\forall\ (i, j, t, y)$

Equations:
(6.20) and (6.21) $\forall\ (j, t, y)$

Equation:
(6.24), $\forall\ (i, t, y)$

Equation:
(6.26), $\forall\ y$

Upper-level constraints:

$$\begin{aligned} &P_{d_{Lower_{Iteration(w)}}}(i,t,y) = P_{d_{Upper_{Iteration(w)}}}(i,t,y), \\ &Q_{d_{Lower_{Iteration(w)}}}(i,t,y) = Q_{d_{Upper_{Iteration(w)}}}(i,t,y), \\ &P_{dg_{Lower_{Iteration(w)}}}(i,t,y) = P_{dg_{Upper_{Iteration(w)}}}(i,t,y), \end{aligned} \quad \forall\ (i,t,y) \tag{6.52.2}$$

Equation (6.52.2) establishes that the demanded power and generation from DG in the lower-level sub-problem in iteration w are obtained from the results of the upper-level sub-problem in iteration w.

It is noteworthy that the upper-level sub-problem cannot be decoupled in time since the periods are interdependent. In turn, the lower-level sub-problem can be decoupled for enhanced computational performance.

6.6 Case study

Regarding regulatory aspects, the parameters are taken from a concession area in the state of São Paulo, called CPFL Paulista, using official data from the Brazilian Electricity Regulatory Agency (ANEEL) [129], [130]. In turn, concerning operational aspects, the parameters are taken from the IEEE 33 bus system [131], [132]. The original electricity consumption ($E(y_0)$) and grid investments ($B(y_0)$) were scaled down to match the test system. It is noteworthy that the IEEE 33 bus system is a medium-voltage grid. Thus, its energy losses are lower than what is expected in practice, and the difference between the solutions of the first and last inner loop iterations is not very substantial. Even so, the case study aims to illustrate the application of the proposed model, validate it, and demonstrate its potential. The lower-level subproblem was decoupled into $y = 10$ subproblems for enhanced computational performance. Regarding the outer loop, 28 scenarios are assumed to guarantee solid results and a satisfactory view of the uncertainties associated with DG uptake.

The computations for the upper-level sub-problem were carried out with Solving Constraint Integer Programs (SCIP) [133], [134] as a mixed integer non-linear programming (MINLP) solver. In turn, the computations for the lower-level sub-problem were carried out with CPLEX [135] as a linear programming (LP) solver. A computer with an Intel Core i7 2.8 GHz processor and 16 GB RAM was used. All modeling was performed in the General Algebraic Modeling System (GAMS), which has built-in functions for generating pseudo-random numbers [117], [136]. The computational time was about 40 minutes for each scenario, implying a total processing time of about 19 hours for the 28 scenarios assumed.

The interquartile range of the optimal compensation is illustrated in Figure 6.2 for both the first and last inner loop iterations. The last iteration presents a lower compensation since it accounts for energy losses, implying additional costs for the DISCO. Thus, the decrease in compensation aims to offset the additional costs without requiring excessive tariff raises. Moreover, the median compensation is practically constant in the first four years and then decreases steadily until 2031. The relatively high compensation at the beginning decreases the payback of DG systems, thus promoting their deployment. In the end, the probability of DG systems deployment is low, and maintaining a high compensation is not beneficial due to undesirable tariff raises. Although the median compensation is practically constant at the beginning, the interquartile range is wide as it depends on the potential to foster DG. In some scenarios, intensive deployment of DG is feasible, whereas, in others, a high compensation might not influence consumer decision-making significantly. Given that in practice the regulatory agency does not know the scenario that will take place (or the exact behavior of consumers), assigning the median values is the most reliable option, although the stochastic characteristic of the results does provide flexibility.

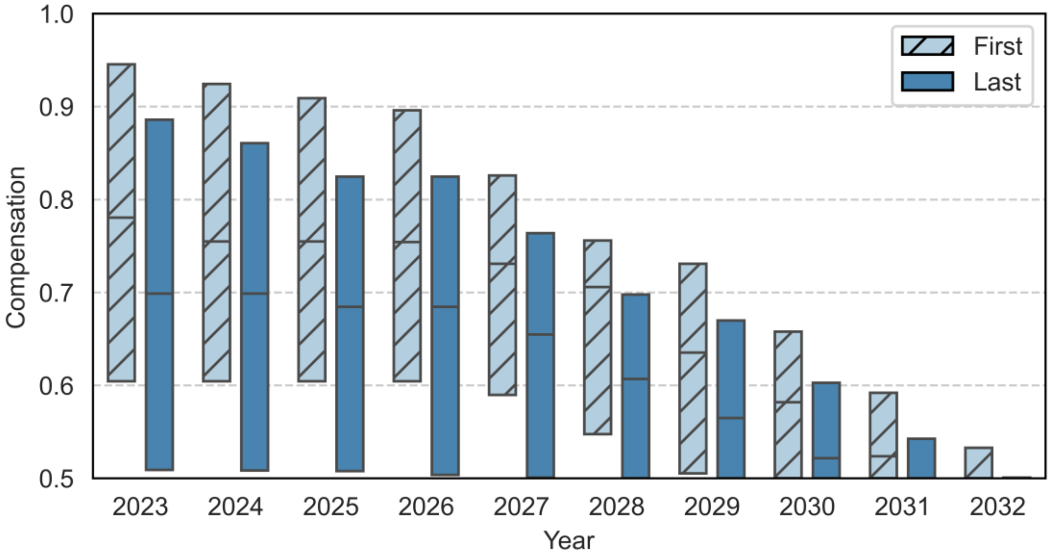

Figure 6.2. Interquartile range of the optimal compensation for the electricity injected into the grid.

The interquartile range of the optimal regulated electricity tariff is depicted in Figure 6.3. The last iteration presents a slightly higher tariff since it accounts for energy losses, but the difference is not excessive since the last iteration presents a lower compensation, as discussed previously. Furthermore, the median tariff increases in the short term to keep up with the high compensation at the beginning and the growth in DG penetration. This is necessary to prevent DISCO bankruptcy, *i.e.*, ensure $EVA(y) \geq 0$. In the medium and long term, the median tariff remains stable since fewer DG systems are deployed and the compensation decreases. In general, limited tariff impacts of around 2.5% are envisaged (median) since excessive tariff impacts tend to harm the objective $EWA(y)$. In particular, excessive tariff impacts reduce electricity consumption and increase tax collection to undesirable levels, typically implying a negative effect on socio-economic welfare. In some exceptions where it is possible to strongly foster DG deployment, significant tariff impacts might take place in the optimization, but these scenarios should not be prioritized by the regulatory agency (the median values should be prioritized). Further studies integrating MOO into the model can prevent significant tariff impacts in some scenarios.

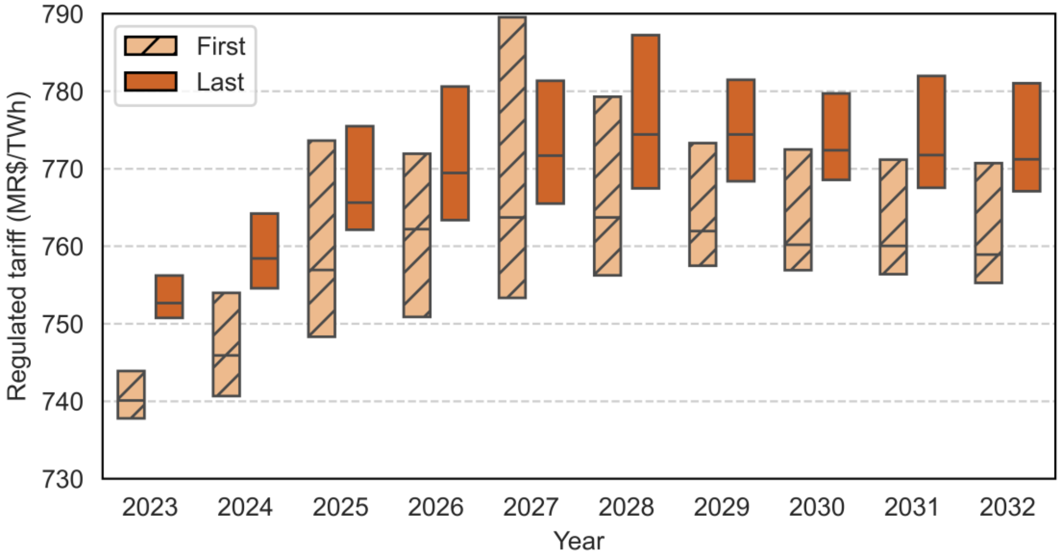

Figure 6.3. Interquartile range of the optimal regulated electricity tariff.

The number of DG systems is represented in Figure 6.4. The difference between the first and last iterations is not significant, as the last iteration presents a lower compensation but a higher tariff. Hence, the payback and the probability of DG system deployment are similar. Moreover, the probability of DG system deployment presents an inverted U-shape, implying that (*i*) the number of DG systems remains approximately constant after 2027, (*ii*) the regulatory agency can be highly certain of DG penetration in 2023 and 2024 (a low penetration is expected up to this period), and (*iii*) 2025-2026 is the most critical period of adoption. Thus, the DISCO should be well prepared to accommodate several connection requests during this period.

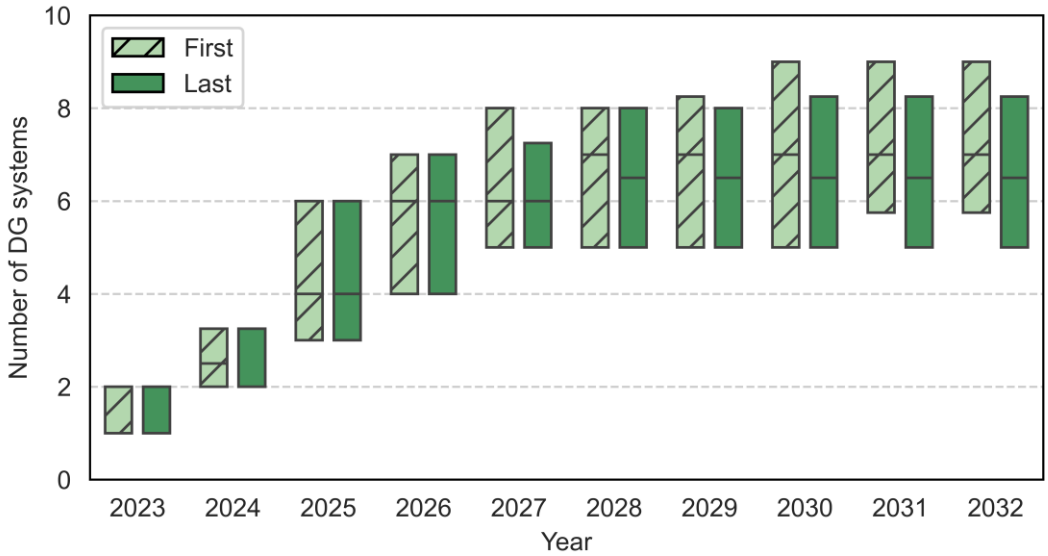

Figure 6.4. Interquartile range of the number of DG systems.

The DISCO surplus is illustrated in Figure 6.5 (last inner loop iteration and with outliers represented). In general, the proposed model aims to achieve $EVA(y) = 0$ to ensure maximum tariff affordability under a sustainable market operation for the DISCO, thus implying welfare maximization. However, some exceptions are verified during the interval with intense DG integration (2025-2028). Such exceptions correspond to scenarios in which consumers are more sensitive to regulatory changes and typically result in high DG integration (8 to 10 DG systems in this case study). Nonetheless, $EVA(y) > 0$ occurs in only 14% of the analyzed scenarios, and it is emphasized that these scenarios should not be prioritized by the regulatory agency.

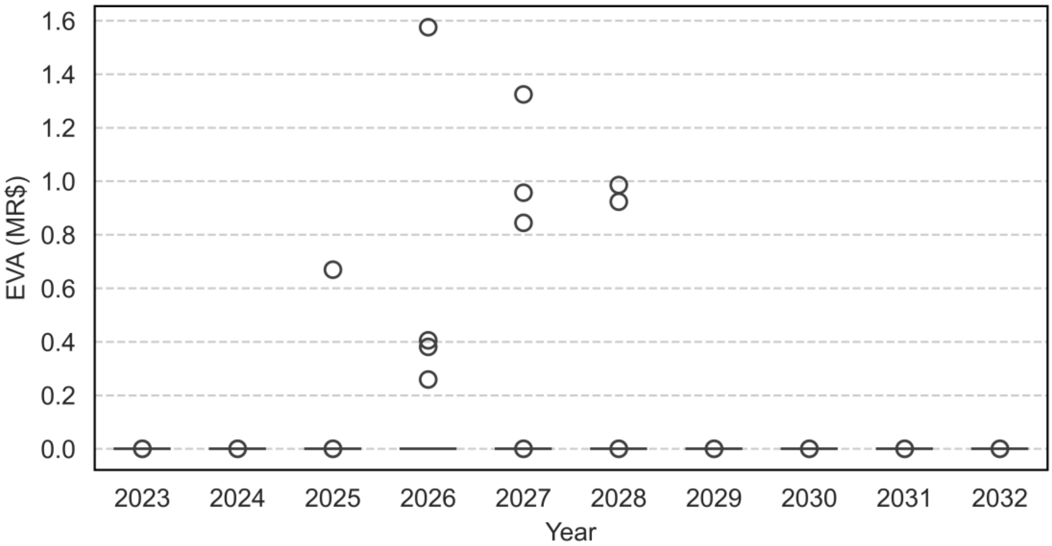

Figure 6.5. DISCO surplus. Last inner loop iteration and with outliers represented.

The relationship between the generated electricity from DG and the objective function is depicted in Figure 6.6 (last simulation year and last inner loop iteration). Figure 6.6 demonstrates that there is a reasonable correlation between the variables ($R^2 = 0.74$), meaning that DG tends to increase socioeconomic welfare.

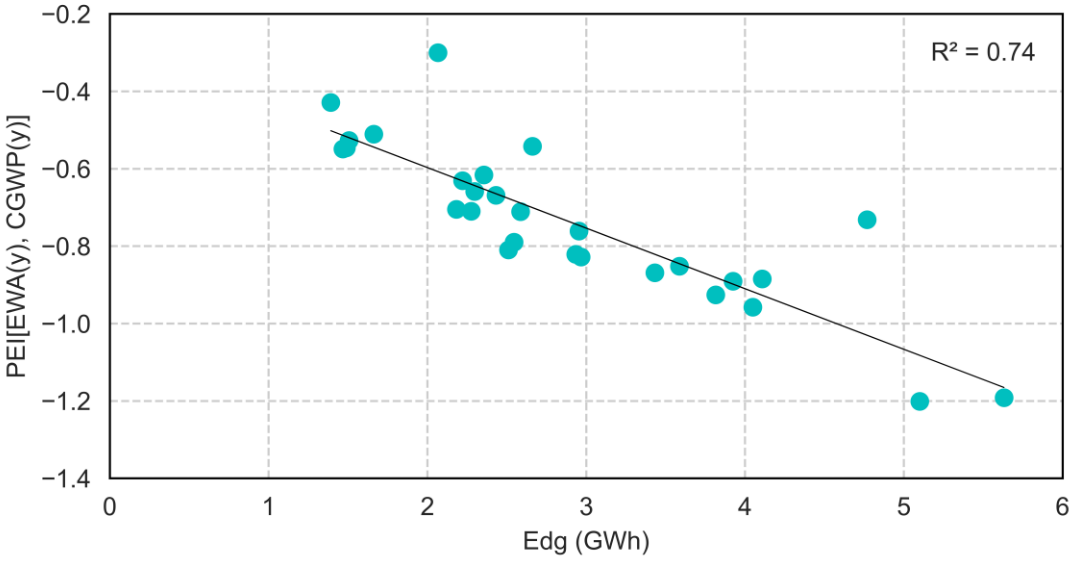

Figure 6.6. Relationship between the generated electricity from DG and the objective function. Last simulation year and last inner loop iteration.

It is essential to evaluate the objective function gain of the proposed model compared to simpler/alternative regulatory frameworks. Hence, the proposed model is compared to three alternative frameworks with preset values of compensation in Table 6.1. The solutions of the alternative frameworks were obtained by predefining the compensation and then running the optimization algorithm. Ordinary Law 14,300 corresponds to the current Brazilian regulatory framework, *i.e.*, a decreasing compensation as follows: 95.9% in 2023, 91.9% in 2024, 87.8% in 2025, 83.8% in 2026, 79.7% in 2027, 75.7% in 2028, and 73% after 2028. For a more thorough analysis, three distinct scenarios are addressed, with minimum, median, and maximum DG penetration (obtained from the 28 scenarios evaluated previously), and the average tariffs of the solutions are also included in Table 6.1. The optimal solution presents objective function gains of up to 9.5%, depending on the analyzed condition. Moreover, it exhibits the second-best tariff affordability with limited losses of up to 3.4% compared to $n(y) = 0.5$. $n(y) = 0.5$ is a detrimental solution in scenarios with a significant potential for DG deployment, whereas $n(y) = 1.0$ is detrimental in scenarios with low potential, in addition to presenting the worst tariff affordability. The effectiveness of Ordinary Law 14,300 also highly depends on the scenario. In particular, the decrease in compensation might occur in convenient or inconvenient periods, highlighting the importance of scientific methods rather than empirical approaches.

TABLE 6.1. COMPARISON OF THE PROPOSED MODEL WITH ALTERNATIVE REGULATORY FRAMEWORKS. LAST INNER LOOP ITERATION.

	$PEI[EWA(y), CGWP(y)]$ (MR$)			$\overline{T(y)}$ (MR$/TWh)		
	Minimum DG penetration	Median DG penetration	Maximum DG penetration	Minimum DG penetration	Median DG penetration	Maximum DG penetration
$n(y) = 0.5$	−0.411 (4.3% loss)	-0.702 (11.1% loss)	-1.090 (8.6% loss)	755.0 (best)	764.2 (best)	782.3 (best)
Ordinary Law 14,300	−0.429 (0.1% loss)	-0.740 (6.4% loss)	-1.079 (9.5% loss)	757.5 (0.3% loss)	777.9 (1.8% loss)	820.7 (4.9% loss)
$n(y) = 1.0$	-0.402 (6.3% loss)	-0.783 (0.9% loss)	-1.181 (0.9% loss)	760.3 (0.7% loss)	779.7 (2.0% loss)	823.0 (5.2% loss)
Optimal solution	-0.429 (best)	-0.790 (best)	-1.192 (best)	757.0 (0.3% loss)	772.9 (1.1% loss)	809.3 (3.4% loss)

This chapter achieved objective (*vi*) and answered RQ5.

6.7 Summary of results and analysis

In this chapter, an iterative bi-level optimization approach for considering the electric grid within the optimization problem was proposed. The results demonstrated that:

- The qualitative results of this chapter and Chapter 5 were similar, as in both chapters there were decreases in compensation and short/medium-term increases in tariffs, followed by tariffs stagnation in the long term;
- The last iteration tends to present lower compensation and higher tariffs than the first iteration, as the last iteration accounts for energy loss;
- Assuming the uncertainty associated with the location and number of DG systems proved to be essential as the optimal decision variables can vary significantly depending on the scenario. However, the case study assumed a very small test system, which can increase the influence of uncertainty due to the smaller sample space;
- In the majority of scenarios, the DISCO surplus was equal to zero. However, exceptions were verified in cases where there is a high potential for boosting DG integration. Such exceptions are unlikely to occur in practice and highlight the importance of running the model for several scenarios and making decisions based on median values;
- By comparing the optimal solution to alternative solutions, objective function gains of up to 9.5% were verified. The electricity affordability of the optimal solution was also satisfactory, although this aspect was not explicitly considered in the objective function.

7 PHILOSOPHICAL REFLECTIONS

Energy access is already well established within the framework of basic human rights [137] since energy is used for numerous day-to-day activities, such as cooking, heating, and lighting, thus being of paramount importance in ensuring a reasonable standard of living. Ensuring access to affordable, reliable, sustainable, and modern energy for all is also established as the seventh sustainable development goal by United Nations (UN) [138]. Due to ease of transport and conversion, electricity stands out among all forms of energy. Consequently, guaranteeing worldwide electricity access is instrumental. According to the UN, however, data concerning energy and electricity access is extremely worrisome [138]:

- 675 million people still live in the dark, 80% of them are in Sub-Saharan Africa. It is noteworthy that people with limited electricity access (electricity needs only partially met) are not accounted for here, making the problem even more worrisome;
- Energy efficiency improvement must more than double its pace (from 1.4% to 3.4% annual improvement);
- 25% of people will still use unsafe and inefficient cooking systems by 2030;
- International public financing for clean energy for developing countries continues to decline;
- Modern renewables power 30% of electricity, but remain low in heating and transport (10% and 4%, respectively).

Therefore, it is clear that the world suffers from serious energy poverty problems. It should be emphasized here that the concept of energy poverty is not only limited to access issues, as energy deprivation can also occur due to a lack of appliance ownership and economic scarcity, as indicated by Bezerra *et al.* [119]. Therefore, whether on a smaller or larger scale, energy poverty is a global problem.

In Brazil, between 750 thousand to 1 million people have very poor or no access to electricity (Paper *g*), the majority living in isolated regions in the north of the country that are not supplied by the interconnected system. Moreover, there are around 14 million consumer units classified as low-income and charged based on the social electricity tariff [139], a distinct tariff that ensures deductions in the electricity bill. However, the effectiveness of the social electricity tariff is limited since the policy requires little electricity consumption for noticeable discounts [17]. Furthermore, Brazil has one of the most expensive electricity tariffs in the world (sixth place according to Marques *et al.* [140]). Such data provide an idea of the scale of the energy poverty problem in Brazil.

By contrast, significant advances in the integration of renewables through DG systems have occurred in Brazil, in which the installed capacity has reached 27 GWp as of February 2024. The scenario “significant advances of DG” on the one hand versus “worrisome energy poverty that is not suppressed at a satisfactory pace" on the other hand is quite ironic, as it states that Brazil has been modernizing its electric sector through emerging technologies but fails to deal with basic problems effectively, such as energy poverty. "More and better energy for the rich and less and poorer energy for the poor" is not an intelligent and sustainable solution!

In this whole context, governmental and regulatory issues are of utmost importance. At first glance, decision-makers should create direct and indirect measures aimed at suppressing energy poverty. While some measures have been implemented in Brazil, such as the social electricity tariff and the "*Luz para Todos*" program, focused on bringing electricity access to remote areas, the aforementioned data supports that further efforts are required for effective energy poverty mitigation. Secondly, given the integration of new technologies and business models and the modernization of the electric sector (which should be encouraged), the regulatory agency has the challenging but essential task of ensuring that the regulatory framework and public policies do not deteriorate social inequalities and consequently electricity affordability for the vulnerable population. The more modern the electric sector (*e.g.*, implementation of CBMs, P2P markets, ESSs, EVs, dynamic pricing, and flexibility markets) the more important but difficult the role of the regulatory agency.

It is emphasized that DG integration in Brazil is not the villain, as DG presents a series of advantages for the system and society (as long as smartly and fairly deployed), as mentioned numerous times throughout this thesis. However, DG integration does require accurate and transparent decision-making by the regulatory agency, which cannot be done through empirical procedures, but only through scientific models with careful evaluation of holistic aspects and overall impacts. Such models should be able to provide impartial solutions that promote the integration of DG smartly and responsibly, compensate prosumers fairly, and limit or eliminate social inequalities and cross-subsidies, thus implying an effective and impartial regulatory framework that considers the interests of all players (consumers, prosumers, DISCOs, government, aggregators, environment, etc.).

The models presented throughout this thesis will not solve such a complex regulatory problem on their own, given the several associated research limitations and improvement opportunities (as per Chapter 8). However, the models function as a satisfactory starting point for having more scientific and well-founded discussions and perhaps encourage new interdependent and multidisciplinary studies on the topic. This is particularly important since the number of studies and models present in the literature does not match the importance of efficient and fair regulation for society. Therefore this thesis raises the ongoing challenge of HOLISTIC DEVELOPMENT OF INTELLIGENT ELECTRICITY MARKETS USING THE TAROT – OPTIMIZED TARIFF – WITH TECHNICAL, ECONOMIC, REGULATORY, AND ENVIRONMENTAL MODELS.

8 RESEARCH LIMITATIONS AND POTENTIAL EXTENSIONS

Some research limitations and future work opportunities are acknowledged below:

• The case studies presented in this thesis were conducted over the span of four years, as the models were developed and tested. Therefore, it is essential to emphasize that some TAROT parameters are outdated, especially concerning the first chapters. Parameters might have changed significantly, meaning that quantitative conclusions reached at the time the study was carried out may no longer be valid. In any case, the models allow for new case studies to be conducted with updated data;

• TOU rates and ESSs are still incipient in Brazil. Thus, due to a lack of historical data, some parameters used to carry out the case studies in Chapter 4 are rough estimations, meaning that such case studies should not be taken as highly accurate in quantitative terms. However, they allow for several qualitative analyses of the effects of DERs on the regulated market and will allow for more accurate studies once TOU rates and ESSs are implemented more commonly and historical data becomes available;

• The TAROT model proved to be a simple and valuable tool for analyzing the impact of rare occurrences, such as the COVID-19 pandemic, on the regulated electricity market and for proposing corrective measures. However, this type of study can be time-consuming since it requires data from tariff readjustment procedures, which are carried out annually. In practice, corrective measures should be implemented quickly. Moreover, natural market changes might affect the results (*e.g.*, economic crises unrelated to the pandemic);

• Simplified modeling for the payback time was considered since the original payback time equation is complex to implement in mathematical programming problems. This might be a topic of interest in the future. Furthermore, the simple payback is an economic index with significant limitations. It was used here since the primary data from ANEEL concerning sensitivity (parameter P_{BS}) is associated with simple payback [29]. However, it may be valuable to model another economic index in the future (*e.g.*, return on investment);

• This thesis did not address approaches for reinforcing, managing, and reconfiguring the grid, which may be necessary in some cases to comply with technical limits, such as cable reinforcement, deployment of shunt capacitors for reactive power compensation, and replacement of transformers. These aspects can be integrated into the lower-level sub-problem so that tariff calculation in the upper-level becomes more accurate (in general, grid investments tend to increase the regulated tariff). Moreover, the modeling of several grid reinforcement approaches can provide an enhanced view of the long-term benefits and drawbacks of DG;

• The case studies assume distributed PV systems since they account for more than 99% of connections in Brazil [100]. If other DG sources are assumed in future work, some parameters should be recalculated, and another LCA should be carried out;

• The impact of shock or surprise due to regulatory changes is not considered in the modeling. However, the shock effect might modify the diffusion curve when new information is available (*e.g.*, the announcement that the OL would be implemented in Jan/2023). Such an effect should be considered in future work;

• This thesis focuses on prosumer compensation and not other aspects of the OL (*e.g.*, legal aspects), which might affect DG integration;

• Although the proposed models enable long-term assessments, it is highly recommended that users apply them annually with updated input data to ensure reasonable accuracy;

• The payback sensitivity (P_{BS}) is an essential parameter in the BDM since it quantifies how potential investors behave in the face of regulatory changes. Although primary data from the regulatory agency was used to estimate P_{BS} [29], advanced market research studies would be important to calculate it more rigorously in the future. It is noteworthy that Brazil is a continental-sized country. Hence, particular characteristics of each region (*e.g.*, income) should be considered since they might affect P_{BS};

• Primary data from ANEEL [29], [100], [109] were mainly used to calculate the parameters based on the procedures described in Papers *a* to *i*. However, some parameters cannot be calculated based on the data currently disclosed by ANEEL. Therefore, such parameters were estimated based on secondary data (Paper *f*). Although necessary in the current Brazilian regulatory context, this approach might influence the results. Hence, it is important to create collaborations with ANEEL in the future to provide researchers with broader access to primary data;

• Although ancillary services applications are a distant reality in Brazil, it might be valuable to integrate them into the model in the future. In this way, prosumers could choose between conventional power injection into the grid, the ancillary services market, or the CBM;

• Brazil implemented measures so that low-voltage consumers can participate in the liberalized market in the medium-term (Decree 465/2019 [141]). Research on the scale of the transition from the regulated to the liberalized market is currently ongoing, as little is known whether the liberalized market will be significantly adopted. Naturally, this is an important topic since such a transition influences electricity consumption and the tariff in the regulated market;

• Concerning environmental aspects, this thesis focuses on GWP. Evidently, other environmental impact categories are also important and should be considered in the future. For instance, human and environmental toxicities might be relevant categories to consider since they are significantly affected by PV generation (Paper g). It is noteworthy that the proposed methodology to quantify environmental impacts (Equation (5.1)) can also be used for other categories;

• A cradle-to-gate + usage phase boundary was assumed for the LCA. Thus, the end-of-life phase (disposal or recycling) was disregarded. It is therefore important to consider this issue in the future, as there will be a massive number of PV modules to be recycled or disposed of, implying significant environmental impacts and logistical problems;

• This thesis did not assume that DISCOs could benefit from avoided carbon costs as an extra revenue. It might be valuable to consider such a policy in the future as it can contribute to enhancing tariff affordability;

• This thesis assumes that there is compensation for the electricity injected into the grid, as is the current regulatory framework in Brazil, but there are other policies/schemes that have not been modeled/analyzed and might be of future interest;

• Integrating local flexibility markets into the proposed models might be beneficial to support the implementation of such markets in Brazil;

• Although the uncertainties related to the location and number of DG systems were considered in Chapter 6, other uncertainties should be incorporated into the model in the future, such as those associated with electricity consumption, irradiance curve, and sizing parameter. As discussed in Paper e, ANEEL started to disclose data concerning the tariff review processes in 2014. Hence, historical series are not particularly extensive, which impairs very accurate risk quantification. Moreover, it might be relevant to address some of the scalars treated as constant in this thesis as time-dependent, particularly the utility function scalars (a, b, a_p, b_p, a_c, b_c);

• The assumed test system in Chapter 6 is very small compared to real distribution systems. Therefore, the assessment of larger systems is important for further developing the subject;

• Concerning Chapter 6, although the lower-level subproblem is already linearized/decoupled and the upper-level subproblem applies linear big M constraints for the binary variables, future works should explore additional approaches to enhance computational performance. Decoupling is not a feasible strategy if energy storage DERs are assumed due to the interdependence between periods. Moreover, the model can become cumbersome depending on the number of buses. Potential solutions include applying grid-reducing methods, utilizing other optimization techniques, implementing scenario clustering approaches, and running the outer loop in multiple machines. Once enhanced computational performance is achieved, it is beneficial to integrate the MOO aspect and CBMs into the model.

• Lastly, converting the scenario-based approach into stochastic programming is promising.

- An important question yet to be investigated is how to deal with the erroneous regulatory allowance for remote self consumption at high compensation levels, which is not within the fundamental premises of sustainable distributed generation, *i.e.*, DG supplying its own loads. The risks of reverse power flow are becoming a reality for some power distribution utilities in Brazil, where centralized DG with remote self comsumption, are injecting power and causing impacts even at the transmission levels. This emphasizes moreover the relevance of regulation on hopefully intelligent electricity markets of the future.

9 CONCLUSIONS

Power systems and electricity markets are undergoing a remarkable modernization process characterized by the increasing integration of several DERs and intermittent renewable generation with automation technologies, the popularization of ancillary services and emerging electricity trading manners, the implementation of advanced tariff schemes, and some degree of market liberalization. This process makes the implementation of effective regulatory frameworks a daunting challenge, given the new market players and stakeholders with distinct interests and the impacts of technologies on power systems. Additionally, the COVID-19 pandemic has shown that the power sector is highly vulnerable to unexpected crises. Thus, decision-makers should be better prepared for the future.

Given this background, empirical analyses are insufficient to regulate electricity markets effectively, but this practice is still common due to a lack of regulatory models to assist decision-makers. Therefore, this thesis developed cutting-edge regulatory models based on the TAROT (socioeconomic regulated electricity market model), BDM (forecasting model of technology integration), and LCA (environmental impact analysis technique). Such regulatory models can be used to assess a range of phenomena and evaluate improvement opportunities, as demonstrated in the several performed case studies. The main conclusions of this study are as follows:

- The COVID-19 pandemic might have significantly affected the Brazilian regulated electricity market. Although ANEEL implemented a short-term public policy (COVID-account) to mitigate the impact of the pandemic, the introduced interest rate will harm consumers for the next few years. Whenever critical events occur, it is necessary to develop holistic, unbiased, and interest-free corrective measures. The TAROT model can be used in this regard, but certain bottlenecks need to be overcome, as discussed in Chapter 6;
- Three potential solutions were evaluated to ensure FEE for the DISCOs in the context of increasing DERs integration: (*i*) modifying tariffs, (*ii*) modifying the compensation for the electricity injected into the grid, or (*iii*) a combination of the two. (*i*) and (*ii*) are relatively simple solutions obtained from a system of equations, whereas (*iii*) is more complex and requires an optimization approach. Regulatory agencies should prioritize more flexible solutions, such as (*iii*), as they may yield superior results. However, they require a thorough understanding of the market and accurate input data to prevent the pitfalls of favoring certain market players;
- The TAROT and BDM suggest that the benefits of DG systems with storage are better exploited in the long term, whereas the benefits of DG systems without storage are better exploited in the short term. Moreover, from the prosumers' point of view, ESSs are not particularly beneficial due to their high CAPEX. However, the regulatory agency can enhance the feasibility of ESSs by increasing the

compensation for the electricity injected into the grid. This approach can be beneficial in promoting earlier integration of ESSs and should be considered by the regulatory agency, but trade-offs in the form of tariff raises should be minimized. In conclusion, the regulatory agency plays an essential role in responsibly promoting the integration of new technologies;

- The OL (regulatory framework recently implemented in Brazil) fulfills its purposes of mitigating tariff increases and reducing social inequality. However, drawbacks in terms of socioeconomic welfare and global warming potential are anticipated. The TAROT model indicates that 91% of DISCOs present positive EVA. Thus, it is debatable whether short-term decreases in compensation are really necessary [18]. In turn, the model estimates a positive EVA for only 63% of DISCOs in the long term (2030), reinforcing that regulatory changes are required before then. Moreover, the approach of assigning a unified regulatory framework for the whole country is detrimental since concession areas are significantly different from each other, and concession areas with incipient DG integration will be discouraged from deploying new systems. Additionally, the OL does not specify its compensation scheme past 2030 (calculation procedure). Such a scheme should be detailed as soon as possible so that there is enough time to propose potential improvements and to decrease the financial risk of investing in DG systems. While reductions in the compensation for the electricity injected into the grid are necessary in Brazil (at least at some point), the OL defined the compensation empirically, without the application of well-defined methods. Naturally, empirical procedures are inferior to scientific methods, particularly regarding market regulation, given its high importance for society;

- The MOO approach indicates that the OL is a dominated or non-optimal solution since it is not located on the Pareto frontiers. Assuming the Euclidian knee points, the optimal solutions implied benefits of around 24% in terms of electricity tariff affordability, with small losses of roughly 6% in terms of socioeconomic welfare and global warming potential, highlighting potential improvement opportunities. Although criticisms of the OL are well-founded, it is acknowledged that political pressure and involvement are notorious in Brazil and might restrain ANEEL from seeking better solutions;

- In the context of increasing environmental concerns, regulatory agencies should consider that their decision-making substantially influences the environment. Promoting the deployment of renewable DG can be an effective measure to assist the energy transition and decrease greenhouse gas emissions, particularly in countries with non-renewable electricity matrices. However, environmental issues are just one of the several aspects to be considered when the implementation of regulatory changes is envisaged;

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[18] It is noteworthy that this conclusion was drawn in 2022, when DG installed capacity was much smaller. In 2024, the need for changes is clearer.

- In the context of CBM implementation, the proposed model indicates that it is beneficial to foster conventional markets in the short term by increasing the compensation for the electricity injected into the grid since this process boosts the DG installed capacity and ensures early benefits for prosumers and the environment. In turn, such compensation should be decreased in the medium term (when the DG sector is already well developed) to foster CBMs. This strategy limits tariff raises induced by high compensation and promotes electricity commercialization between prosumers and consumers at affordable prices, thus contributing to energy poverty mitigation;
- CBMs can enhance electricity affordability in Brazil by approximately 1.9% assuming the entire regulated market, or 13.6% considering only the CBMs participants. Therefore, the benefits of such markets in mitigating energy poverty are clear. Nevertheless, they are not expected to solve the problem alone due to the limited amount of electricity to be commercialized. Consequently, decision-makers should consider implementing additional measures (*e.g.*, subsidies) for further energy poverty mitigation;
- It is essential to implement policies to ensure that low-income consumers can participate in CBMs. Otherwise, CBMs might intensify energy poverty due to regulated tariff raises. Therefore, regulatory agencies should think about effective ways of implementing CBMs beforehand;
- In a conventional market structure scheme, DERs tend to harm DISCOs economically, leading to tariff raises. One of the biggest regulatory dilemmas is how to simultaneously foster the integration of DERs and ensure electricity affordability for conventional consumers. Even with the development of cutting-edge regulatory models, there is no simple answer to this. Human experience and expertise are also essential and should be used alongside models (*e.g.*, defining the suitable solution of the Pareto frontier). Decision-makers should focus on developing holistic, unbiased, effective, and transparent regulatory frameworks considering the common good of the community and the environment;
- The iterative scenario-based bi-level optimization approach demonstrated the potential of advanced regulatory models, as they can lead to better solutions and an enhanced understanding of the market. In particular, advanced models that represent the electrical grid within the optimization problem are very promising, given their accuracy and flexibility. Nonetheless, some similarities in qualitative results were verified concerning Chapters 5 and 6, with both indicating that medium-term decreases in compensation and slight short-term tariff raises would be adequate. This suggests that simpler models are also useful and provide a satisfactory overview of the market. Moreover, simpler models present better computational performance;

Lastly, based on the several described research limitations in Chapter 8, one can conclude that an important burden to overcome is tuning all parameters accurately and transparently based on reliable and official data. If this process is achieved in the future, the models presented herein can lead to more precise solutions.

10 DATA AVAILABILITY

The detailed cradle-to-gate LCI used in this thesis is available in the supplementary material of Paper g (Tables 15 to 21 and 35 to 39). However, transportation requirements and the amount of PSH in each concession area vary. Such information is available in [112]. Moreover, reference [112] also contains the TAROT model parameters for the 35 concession areas analyzed in Chapter 5, which were mostly calculated based on primary data from ANEEL [29], [100], [109]. Regarding the parameters $EF(r)$ and $W(r)$ used to quantify energy poverty issues, the data was organized in reference [142]. Lastly, the data used in the case study of Chapter 6 is available in [143].

The references provided in the previous paragraph concern the main data used, but additional information (*e.g.*, the parameters calculation procedure) is available in Papers *a* to *i*.

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