A Future-Looking Methodology for Estimating CO_2 Emissions Reductions Linked to Transmission Projects That Increase Renewable Generation Capacity

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***Abstract*—This paper introduces a methodology that allows for the estimation of the reductions in systemic CO_2 emissions associated with transmission projects that increase the dispatch of renewable generation in a given region in a future time horizon. This methodology relies on stochastic dual dynamic programming, and by providing quantitative results, reinforces the fundamental role of transmission expansion in the transition towards a scenario of increasingly sustainable grids. This work also presents a case study that consists of estimating the reduction of emissions involved with transmission projects in Southeast Brazil that will enable the flow of +615 MW of photovoltaic and +261 MW of biomass thermal generation, in a future horizon covering eight years. The main results are that the new transmission projects contribute to an average net reduction of about 1.128 million tons of CO_2 emissions over the horizon and that, in less than four years, these projects will offset the emissions from their implementation and construction.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/10236

***Index Terms*—Energy transition, variable renewable generation, power transmission expansion, reduction in CO_2 emissions.**

I. Introduction

A. Motivation

RENEWABLE generation is the primary driver in the transition towards sustainable power grids. Clean energy sources replace conventional fossil fuel-based generation, thereby reducing emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) [1]. In many cases, however, renewable generation plants are installed far from consumption centers, requiring the construction of transmission lines and facilities. Also, there are instances where the amount of sustainable generation being connected encounters a power system that cannot reliably accommodate this generation, so new transmission infrastructure is needed [2]. Hence, new transmission projects that increase renewable generation are also fundamental in reducing CO_2 emissions [3].

This way, this work's motivation is to reinforce the fundamental role that the transmission expansion plays in the energy transition. It aims to contribute by providing a novel methodology that stochastically considers a future horizon and quantitatively estimates the reduction in CO_2 emissions (actually of CO_2-equivalent emissions, so that the rest of the GHGs are also always considered) associated with a given project or set of transmission expansion projects that increase renewable generation capacity. This methodology shows that even small transmission projects, provided that they guarantee the secure connection of renewable generation, can contribute.

B. Literature Review

Around the world, recent research have demonstrated that expanding transmission infrastructure is mandatory for greater integration of renewables and reducing CO_2 emissions.

For instance, [4] combines a multi-market energy equilibrium model and a bottom-up stochastic model focusing on the European electricity and district heating sectors to examine the role of energy storage and the construction of international transmission lines to help the European Union (EU) meet its CO_2 emission reduction targets for 2030 and 2050. The authors conclude that by 2050, the transmission grid capacity must increase by 4 to 6 times compared to the capacity from 2015. Then, [5] introduces a new framework for assessing the future needs of power grids, highlighting the complementary roles of energy system and power grid models. Analyzing the EU power system, the authors argue that to achieve a net-zero system by 2050, transmission capacity must at least triple to 200 GW (considering the capacity of 70 GW from 2020).

Reference [6] investigates decarbonization pathways for the European power market, considering varying levels of political and physical collaboration (with physical collaboration referring to transmission expansion). The authors discuss how countries with substantial renewable energy resources (solar and wind) can enhance their deployment of renewable generation when cross-border transmission is improved. Complementarily, [7] illustrates how the electrification of industries

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such as steel, cement, refining, and chemical processing can support decarbonization. The presented case study focuses on Sweden's basic industry and concludes that industrial electrification can facilitate the integration of renewable generation and energy storage. However, the authors emphasize that the pace of industry electrification depends entirely on the speed of power transmission infrastructure expansion.

The authors of [8], when studying the Texas and Mid-Continent electricity markets, show how transmission constraints reduce the environmental benefits of renewable generation, concluding that transmission expansions are the main factors that enable clean sources to replace more fossil generation and reduce emissions. Reference [9], then, analyzes how the existing transmission infrastructure in the United States (US) for that country to achieve net-zero CO_2 emissions by 2050 is insufficient and points out that even the least aggressive scenario implies in more than a doubling of the current transmission capacity by that year. The authors of [10], in turn, investigate the relationship between transmission expansion and the dissemination of renewables in Colombia. They conclude that expanding power transmission systems is essential for integrating clean generation plants and that the speed at which new transmission projects are built to accommodate renewable generation is also a determining factor regarding emissions. This is because, with a delay in the transmission projects, not all of the installed renewable generation capacity can be generated, and the portion not generated will certainly be replaced by conventional thermal generation in other locations.

Reference [11] introduces a two-stage min-max-min model designed to co-optimize the expansion of both the transmission system and renewable generation capacity, ensuring that renewable energy targets are met while adhering to high security standards and addressing uncertainties related to renewable resources. Through a case study of the Chilean energy system, the authors demonstrate the importance of coordinating the growth of renewable energy with transmission expansion planning. However, the study does not address how the joint expansion of transmission infrastructure and renewable generation reduces emissions.

Regarding the Brazilian energy system, [12] present an open-source, academic, multi-year, two-stage generation and transmission expansion planning software that enables automated measurement of CO_2 emissions from the expansion and import of the existing system, as well as the evaluation of environmental policies to reduce emissions and the identification of transmission bottlenecks between subsystems. A case study shows that expanding the transmission grid must accompany the expansion of renewables. Still, even though the proposed software allows estimating reductions in emissions, the authors do not focus on this and do not discuss the results (the main focus is reliability). Then, the authors of [13] discuss how the growth in wind power generation requires transmission expansion and present a probabilistic approach to demonstrate how the optimal transmission expansion plan can be affected when accounting for wind generation variability. However, as in [12], the focus is on the reliability and investment in the power system, rather than on emission reductions. Complementary to this, [14] analyzes the least-cost composition and operation of a fully renewable power supply system as part of a 100% renewable energy-based system in Brazil. It relies on a high-resolution energy system model, which considers the power sector and all links to the heat and transport sectors. The results indicate that a completely renewable power system in Brazil is theoretically possible, but with additional transmission. Still, it also does not consider results on emissions reductions.

Regarding China, the authors of [15] suggest that a key action for the future low-carbon development of the power sector is to actively promote the construction of large-scale clean energy transmission channels by 2030, to prioritize the delivery of sustainable energy while continuously improving the capacity for mutual aid and guaranteeing power supply. Additionally, [16] presents a decarbonization model for the current Chinese power sector. The authors emphasize the necessity of building and enhancing cross-regional power transmission infrastructure, particularly ultra-high voltage transmission lines, while also encouraging local governments to support the development of renewable energy sources.

Reference [17] discusses the benefits of high-voltage direct current (HVdc) transmission over long distances and explains that new HVdc projects can serve to integrate remote renewable sources, thus contributing to reducing emissions. According to the authors, "if its (in this case, HVdc transmission) use helps in reducing CO_2 production by helping replace fossil fuel-based generation, its help on the environmental impact is extremely high." The authors provide results of CO_2 emission reductions associated with two existing HVdc line projects in China that replace conventional fossil-based with renewable generation. Using historical data from 2003-07, the authors of [18], then, conduct an econometric analysis based on the time-varying difference-in-differences method to analyze how much the construction of new transmission lines between Chinese provinces contributed to reducing emissions. They compare emissions from a system involving nineteen provinces in which lines were built between 2003 and 2017 with emissions in the same period from another part of the system, in which inter-provincial lines were only built only in 2021. The main conclusion is that the lines have significantly reduced the amount and intensity of regional emissions.

C. Research Gap

From the bibliography review, one can see that the expansion of transmission is fundamental in reducing emissions and eventually reaching net-zero, in different parts of the world. More than one reference detail that, to achieve the desired decarbonization goals, existing power transmission facilities must grow substantially (at least triple in the EU, according to [4] and [5], and double in the US [9]) in the coming years. At the same time, and in a complementary way, references such as [7] and [10] show how the speed of implementation of new transmission projects is decisive in connecting new renewable sources and consequently reducing CO_2 emissions. Also, [17] and [18] provide numerical examples on how existing and already concluded transmission expansion projects in China indeed contributed for reducing CO_2 emissions.

The cited references discuss how the expansion of transmission is essential in the transition towards sustainable and net-zero power grids. However, it is necessary to point out that a large-scale and accelerated expansion of transmission lines and substations is not a trivial task, especially when the expansion involves doubling or tripling the existing capacity. Transmission expansion projects are complex and challenging for several reasons, such as engineering, equipment manufacturing and transportation, land and property issues, and public acceptance [9]. Also, the construction of power transmission projects also have significant CO_2 and GHG emissions that cannot be ignored. In this context, the authors of [19] provide a framework that accurately accounts for CO_2 emissions associated with the implementation of new transmission facilities (mainly lines) at all stages of the project (production, transportation, and construction). The authors use examples of typical projects to demonstrate how much each phase contributes to total emissions and to provide insights and recommendations for reducing them. Reference [20], in turn, introduces an approach to estimate transmission projects' (mainly substations and transformers) emissions by extending the life cycle approach. The authors divide the cost and emissions model into five phases (production, transportation, installation, operation and maintenance, and discard or recovery) and provide a comprehensive tool for transmission utilities to determine the emissions of their existing and future projects.

One can see, therefore, that there is a need for a methodology explicitly designed to quantify the contribution of each transmission project within a large-scale expansion plan aimed at enhancing clean energy production within a given system to future decarbonization efforts. A clear methodological framework that produces tangible results and shows how even small grid expansion projects can significantly lower future emissions would help tackle challenges related to large-scale expansion, such as achieving public acceptance. Further, direct evidence that a future transmission project will contribute to reducing emissions could attract more utilities and engineering firms interested in undertaking the project, ultimately lowering costs for consumers. However, to the authors' knowledge, no such methodology currently exists.

D. Contribution

Finally, this article aims to contribute by precisely introducing a novel and straightforward methodology designed to estimate, over a predetermined future time horizon, and in a stochastic manner, the reductions in CO_2 emissions associated with a given transmission expansion project or set of projects that increase the flow margin of renewable generation in a power system. This methodology has six steps and uses the established stochastic dual dynamic programming (SDDP) technique, and aims to be simple to implement and reinforce the fundamental role of transmission expansion aimed at greater integration of renewables by showing, with direct numerical results, that future transmission projects, even small ones in a larger-scale plan (as those proposed in [4]- [16]), are significant for emissions reduction. By using a stochastic approach, this methodology can capture different patterns of variable renewable generation output, hydrology, and load profiles, which is fundamental according to [4]. It shows how a set of transmission expansion projects that increase renewable generation enhances the capabilities of energy management, which then results in reductions in CO_2 emissions. As an application example, this work also presents a case study in which the methodology was used in a region of interest that represents a strategic frontier for the Brazilian energy transition. The current inadequacy of the grid in this region leads to curtailment or sub-optimal dispatch of clean sources, making it the ideal testbed for a methodology that quantifies how infrastructure unblocks suppressed renewable potential.

The methodology proposed in this work complements the discussions and results of the bibliographical references, but with the difference that the methodology proposed here can be applied to electrical energy systems anywhere in the world, with diverse generation matrices, and that the proposed approach also considers the CO_2 emissions linked with the construction of new power transmission expansion, which is not taken into account in [4]- [16]. At the same time, regarding the differences between the present work and references [17] and [18] (which, like this article, provide numerical results of reductions due to transmission expansion), the following main differences can be outlined:

- Unlike [17], which focuses only on the impact of HVdc transmission, the methodology proposed in this work can be applied to evaluate the effect, in terms of emissions reduction, of any transmission project (new lines, transformers, etc.). Furthermore, unlike [17], in which the authors do not present the horizon in which the reduction in the emissions would occur (in one year, in ten years, etc.) nor discuss if it is a past or future-looking horizon, this methodology allows the user to see what the average, maximum and minimum reductions are per month or year of the future horizon.
- Unlike [18], which presents a study that looks at past data and performs a retroactive analysis comparing emission reductions in different parts of the system, the proposed methodology, in a complementary way, looks to the future. It considers a stochastic approach, in which aspects such as hydrology and the availability and variability of renewable generation vary in each possible series. It compares the same energy system with and without the energy effect of new transmission lines that increase the flow capacity of renewable generation in the same scenarios.

Finally, to compare this research's contribution against the existing literature, please refer to Table I. Also, please note that Section II describes the methodology's steps; Section III describes a case study in which the proposed methodology was applied; Section IV describes the results; Section V presents discussions regarding the case study and the methodology's limitations; and Section VI concludes this work.

II. Methodology

This section provides a detailed description of the methodology proposed in this research. In this context, please refer to Fig. 1, which illustrates a schematic flowchart depicting the six steps of the methodological framework. Each step includes an input, an action, and an output. Still, before delving into each of the methodology's steps, it is important to note that

TABLE I
COMPARATIVE TABLE BETWEEN THE LITERATURE REFERENCES AND THE PRESENT WORK

Reference(s)	Contribution
[4], [5], [9]	Show how, to reach the desired net-zero targets, the capacity of existing transmission grids must increase significantly in size.
[6], [8], [11]–[16]	Discuss how expanding transmission infrastructure to connect new renewable generation (and thus reduce emissions) is fundamental.
[7], [10]	Show how the speed in the implementation and construction of transmission expansion are decisive for the electrification of the industry [7] and the expansion of renewables [10], and therefore for decarbonization.
[17]	Shows how long-distance HVdc transmission can bring clean generation to remote points, thus replacing fossil fuel-based generation and reducing emissions, and presents data from real projects in China.
[18]	Shows, using historical data and an econometric analysis, how existing inter-provincial lines in China reduced CO_2 emissions.
This article	Proposes a new methodology that estimates the future contribution in emissions reductions of a new transmission expansion project, is simple to apply, and could help overcome some of the difficulties inherent in constructing new infrastructure. Complements the contributions of [4]- [16] and, unlike [17] and [18], proposes a that looks at the future, not at the past.

it utilizes and relies on a technique known as stochastic dual dynamic programming (SDDP). The proposed methodology does not modify the well-established SDDP technique but employs it as a tool. So, an overview of it is provided below.

The SDDP, initially proposed in [21], is a sophisticated mathematical programming and optimization tool designed to determine the optimal operating policy for hydroelectric reservoirs and thermal power plants over a predetermined future time horizon. This is achieved using historical data of variables such as renewable and fossil fuel-based generation, hydrology, load, energy and fuel prices, and the volumes and capacities of reservoirs. The SDDP is a powerful resource for power system operators and planners, enabling them to make informed and robust decisions for managing water and thermal resources sustainably and cost-effectively. For decades, system operators worldwide have utilized it to optimize hydrothermal dispatch and energy planning. At the same time, it remains prevalent in recent research [22], [23].

The simulation of an SDDP model consists of two rounds. In the first round, the SDDP algorithm develops the energy policy for operating the reservoirs of the studied system's hydroelectric power plants. This policy, which aims to obtain the operating strategy that meets the demand for energy at the lowest cost over the horizon, is based on evaluating the cost of using the water from the reservoirs and operating the thermal plants over time in a series of scenarios that SDDP algorithms generate, based on historical data of factors such as hydrology and renewable generation parameters. In the second round of an SDDP model's simulation, the policy is then assessed against new time series, in which parameters such as river and river basin flows vary from series to series.

There are different software programs that run SDDP models used to optimize the hydrothermal dispatch of a power system. In Brazil, for example, both the Newave, developed by the Electric Energy Research Center (Cepel) [23], and the SDDP software from the consulting firm PSR [24] can be employed. The Brazilian Energy Research Office (EPE), responsible for the country's energy planning, provides official databases for these two tools [25]. Hence, with the SDDP database (files with simulation configuration, generation data, hydrology data, load data, renewable generation data, study horizon, fuel data, among various others) and software that runs this algorithm, the user can then proceed to the methodology's six steps. Still, please note that the SDDP is employed solely to optimize the hydrothermal operation policy and does not involve the optimization of the transmission expansion itself. The transmission expansion projects are treated as static inputs derived from external planning studies. The proposed methodology is an assessment of a pre-defined expansion plan, rather than a transmission expansion planning optimization model. Besides, since the methodology considers as input an already optimized transmission expansion plan, that is, a set of new transmission projects that guarantee a set of new renewable plants, the SDDP does not consider that there may be a violation of the physical limits of the transmission network under consideration. Therefore, for this methodology, the SDDP relies only on a simplified transport model (mass balance) between regional subsystems.

Furthermore, please be informed that the methodology assumes that the additional renewable generation primarily displaces only fossil-fuel-based thermal generation, so that the reductions in emissions depend on this structural modeling assumption rather than on an endogenous decomposition between hydro and thermal displacement.

Step 1: in this step, from the SDDP database (input), the user simulates the operational policy of the reservoirs and thermal plants (action) to obtain, in the corresponding files, the policy for the system under study in the horizon considered (output). The policy will consider all generation and interconnection restrictions between subsystems and scheduled generation and transmission expansions the user provides.

The presented methodology does not consider the transmission projects directly but rather their energetic effect on the energetic system under analysis. The impact on the energetic system that the new power transmission projects that increase renewable generation capacity have can be represented by equivalent renewable power plants. This will be further detailed in the case study presented later.

Step 2: consists of performing the second stage of the SDDP model simulation (stage in which the policy resulting from step **1** is assessed against new time series), with the same generation data from the initial database, that is, without considering the equivalent renewable plants. The data files corresponding to the policy and the original database are the inputs of this step, the simulation of the second stage of the SDDP is its action, and its output are the CO_2 emissions of

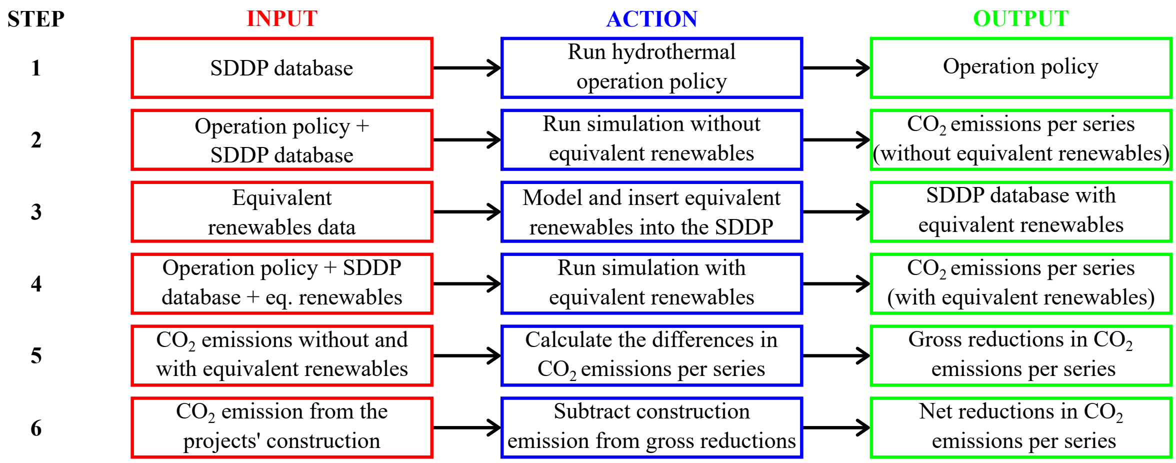

Fig. 1. Steps of the proposed methodology. Each has an input, an action, and an output, and must be processed in order (**1** → **6**).

the thermal plants by series (for this, the user must inform the type of fuel in each thermal plant and its respective CO_2 emission factor). These are the system's emissions without the effect of the new transmission projects.

Step 3: concerns the equivalent renewable plants, which, as mentioned, represent the effect of new transmission projects. The generation values corresponding to these equivalent plants must be calculated before applying the proposed methodology, in the transmission expansion planning studies that consider the expansion of renewable generation. Using the data regarding the equivalent renewables (capacity and generation curves, among others), which are the inputs of this step, the user inserts and models them in the SDDP (action), thereby obtaining the SDDP database with the equivalent renewables (output). It is noteworthy that the considerations, criteria, and assumptions used in the equivalents' renewables modeling are decisive in the results. Hence, this step must be performed carefully and coherently by the user.

Step 4: the inputs of this step are the policy established in step **1** and the database with the equivalent renewables obtained in step **3**. With those inputs, the user then re-simulates the second stage of the SDDP (action), with the same series as in step **2**, but with the new database. The simulation yields the system's CO_2 emissions per series, but in this case, with the equivalent renewables duly considered (output).

Step 5: with the emissions per series obtained both with and without the equivalent renewables, which are the inputs of this step, the user then calculates, for each series and each year or month (depending on the size of the future horizon), the differences between the CO_2 emissions (action), finally obtaining the gross reductions in emissions per series (output). It is worth noting that this step's output is regarded as gross reductions in CO_2 emissions at, until this moment, the CO_2 emissions associated with the transmission projects' implementation and construction were not considered.

Step 6: in this final step, the net reductions in CO_2 emissions in each series are determined. The emissions related to the implementation and construction of transmission expansion projects are subtracted from the gross reductions obtained in the previous step. It is worth noting that, in step **5**, the user obtains the reductions per year in each series, so that with the emissions associated with the implementation and construction of the projects, it is possible to predict how long it will take for the new transmission facilities to offset their emissions.

The emissions related to the implementation and construction of the projects can be obtained, for example, from GHGs emissions inventories of the transmission utilities and project reports. If no information is available, however, and the user still wants to obtain some estimate of the emissions from these engineering stages, it is recommended to consult references [19] and [20] and use the values obtained therein. Also, it is worth noting that to further enrich the analysis, the emissions associated with the construction of the renewable plants themselves could be considered if the data is available.

III. Case Study

The Brazilian energy system, known as the National Interconnected System (SIN in Portuguese), had over 248 GW of installed generation capacity in February 2026. Approximately 90% of this capacity comes from renewable sources, and this percentage is expected to rise in the coming years. By 2030, the National System Operator (ONS in Portuguese) forecasts that the total installed capacity in the SIN will exceed 272 GW, with around 93.5% of that capacity attributed to renewable energy. Additionally, it is important to note that the SIN currently operates a transmission network at voltages ranging from 230 to 800 kV. As of February 2026, this network extends over 176,000 kilometers, and by 2030, the ONS predicts an increase of approximately 8,000 kilometers [26].

The SIN comprises four main subsystems (north, northeast, southeast, and south). These are interconnected by specific transmission lines. Fig. 2 provides a map in which each subsystem is located and identifies the interconnections (dashed lines). The region where the borders between the southeastern states of Mato Grosso do Sul (MS), São Paulo (SP), and Minas Gerais (MG) meet, marked as "Region of interest" in Fig. 2, has high potential for the installation of solar photovoltaic power plants, due to the high levels of yearly solar radiation and low costs. It also has extensive sugarcane fields and, consequently, several combined heat and power plants, which produce electricity from sugarcane bagasse.

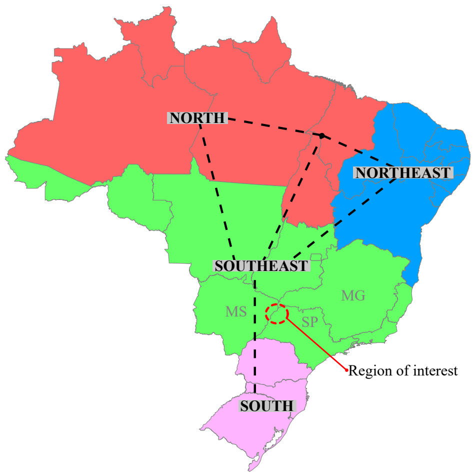

Fig. 2. Map of Brazil representing the energy subsystems, interconnections, and the region of interest of the case study.

In recent years, the number of solar photovoltaic and biomass thermal generation connections in this region has increased significantly for the abovementioned reasons. For example, when browsing the web map of the geographic information system for the energy sector in Brazil [27], provided by the Energy Research Office (EPE in Portuguese), one can notice that, in this region, between 2019 and 2025, there was an increase of more than 700 MW in solar photovoltaic generation and that, between 2017 and 2020, there was an increase of more than 350 MW in biomass thermal energy (mainly sugarcane bagasse). However, the current transmission system in this region is inadequate to safely and reliably transport all the volume of renewable generation being connected. For this reason, many renewable plants encounter generation limitations.

In this context, the EPE conducted a transmission expansion planning study whose objective was to obtain the most appropriate set of transmission projects so that the resulting transmission system could handle all the renewable generation being connected [28]. In total, EPE determined nine new transmission projects for this region. Once all these new projects are completed (their completion is, in this case study, assumed to be in 2026), the electrical system of the region of interest will be able to accomodate, reliably, +615 MW of solar photovoltaic generation and +261 MW of biomass thermal generation than it can today (the plants already in operation will be able to increase their generation and new plants will be able to be connected). The total investment cost of these new transmission projects is 407 million Brazilian reais, which corresponds to approximately US$ 74 million.

Please refer to Fig. 3, that shows, in addition to the existing system in the region of interest, the new projects to be implemented so that the system can accommodate +615 MW of solar photovoltaic and +261 MW of biomass-thermal generation. Fig. 3 also shows how much solar and sugarcane bagasse generation can be connected to each of the 22 buses of the system once the projects' implementation and construction are completed. The new projects, described next, comprise an increase of +700 MVA in power transformation capacity and works on more than 140 km of lines.

- Installation of a transformer between buses **01** and **12**, 500-138 kV, 60 Hz, and rated capacity of 400 MVA;
- Installation of a new transformer between buses **02** and **12**, 440-138 kV, 60 Hz, and rated capacity of 300 MVA;
- Construction of a new line between buses **03** and **04**, 440 kV, 60 Hz, 38 km, and rated capacity of 1524 MVA;
- Reconstruction of the double-circuit line between buses **12** and **13**, 138 kV, 60 Hz, 7 km, for the capacities (normal/emergency) of 249/293 MVA each;
- Reconstruction of the double-circuit line between buses **13** and **15**, 138 kV, 60 Hz, 48 km, for the capacities (normal/emergency) of 139/163 MVA each; and
- Reconstruction of the double-circuit line between buses **19** and **21**, 138 kV, 60 Hz, 50 km, for the capacities (normal/emergency) of 206/242 MVA each.

Hence, and as case study, the authors chose to apply the methodology proposed in this research to estimate the impact, in terms of CO_2 emission reductions, of the +615 MW of photovoltaic and +261 MW of biomass-based thermal generation that will be connected to the system as a result of the new transmission projects in the region of interest.

It is important to note that the proposed methodology also aims to demonstrate that any expansion of the transmission infrastructure built to increase sustainable generation capacity at a given point in the power grid will contribute to reducing CO_2 emissions in the future, no matter how small it may be within a larger transmission expansion plan. This is just the case of the projects selected for the case study, since there are currently many transmission expansion projects to accommodate more renewable generation in Brazil. According to the EPE, the current total investment in transmission for the connection of new renewable sources, considering Brazil as a whole, is around US$ 11 billion, and all of these projects will allow the connection of an additional 46 GW of renewable energy. Thus, the projects discussed in the case study are small compared to the larger expansion plan. Even so, applying the methodology in their context allows to show that they will also contribute to reducing emissions.

In fact, it makes more sense, with this methodology, to analyze small transmission projects individually, as in a vast expansion plan like those suggested by [4], [5], [9], the deadlines and complexities in implementing each project, as well as the transmission and engineering companies responsible, vary significantly. Applying the methodology to small projects individually allows the evaluation and precise estimation of the contribution of each pack of transmission expansion projects.

This case study used the SDDP from PSR [24] and the EPE's database for this software [25]. Yet, as previously mentioned, other programs that implement the SDDP model and database could be used. In this specific case, the authors chose to use EPE's database because this is the agent primarily responsible for planning the expansion of the electricity sector in Brazil. With it, the steps were then performed.

Step 1: for the determination of the optimal hydrothermal dispatch policy (step **1**), the authors used the default settings of the EPE's database. The first simulation year was 2025, and 30 years of future horizon were simulated, with 1200 series.

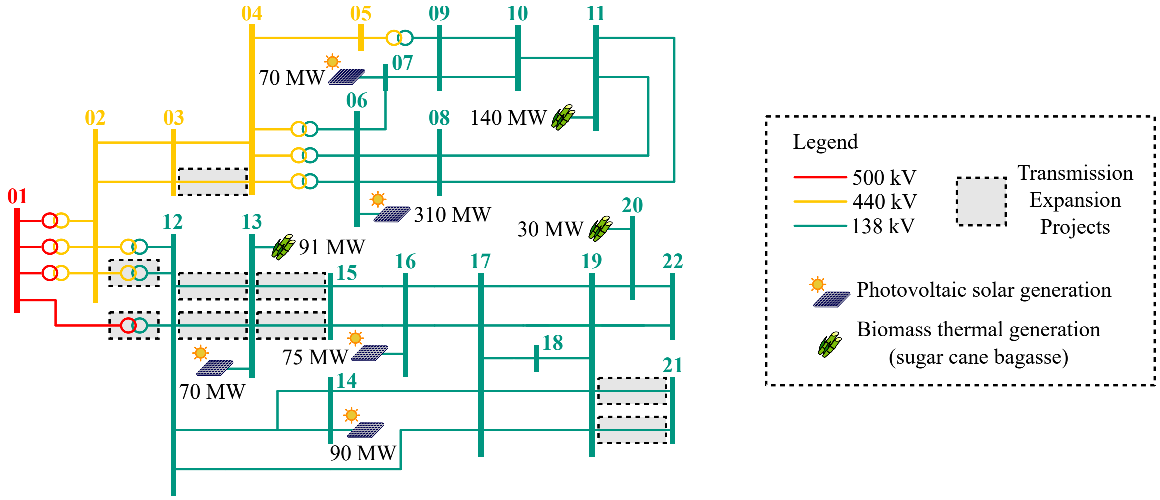

Fig. 3. Existing transmission system in the region of interest. The highlighted lines and transformers indicate the locations of the transmission expansion projects. The numerical indications for renewable generation represent the amount of power that can be connected at each point after these projects are completed.

The series are generated by SDDP from historical data on hydrology and renewable generation parameters. To obtain the policy, 12 stages were simulated per year (twelve months). The authors stored the files generated by the SDDP simulation containing the policy and proceeded to step **2**. For the policy simulation, a PC equipped with an Intel(R) Xeon(R) W-2223 CPU running at 3.60 GHz was used. The simulation lasted six hours; still, this time may vary depending on the hardware.

Step 2: in this step, the operating policy for hydroelectric reservoirs and thermal plants over time determined in step **1** was tested against 200 new series that could occur in the future. An eight-year horizon was considered, starting in 2026. From this point onwards, year N, with N = $\{1, \cdots, 8\}$, represents the N-th year after the initial year. Each year is modeled as a set of $24 \cdot 365 = 8760$ hours (hourly modeling). Hourly modeling, typically not used in the policy determination, where more years and series are considered, is important in systems with high proportions of non-dispatchable sources, such as solar and wind, whose power outputs vary throughout the day [4].

The main objective of this case study is to present the methodology results as proof of concept. Thus, the authors deemed the future horizon of only eight years sufficient (the longer the future horizon, especially with hourly modeling, the simulation processing time increases non-linearly). For the simulation of the 200 series in this step, using the same PC that was used to simulate the policy, the simulation time was 16 minutes.

In this methodology, the only output of interest of the SDDP simulation is the system's CO_2 emissions in each year (sum of annual hourly emissions) of the future horizon. Hence, this was the only output recorded in this step. However, before step **2** was carried out, the authors registered, in the SDDP, the CO_2 emission factors of the fossil fuels presented in Table II [29]. The fuel used in each thermal plant is information already registered in EPE's database. This way, with the simulation, 1600 annual emission values were obtained. Please note that, in this case study, the system's total operating emissions are attributed entirely to the fossil-fuel-based thermal plants, since their emissions during operation are significantly higher than those associated with other generation methods.

TABLE II

CO2 Emission Factors (in Terms of Tons of CO2 per TJ and per MWh of Thermal Energy Produced) of the Fuels Considered in the Study [29]

Fuel	t CO_2/TJ	t CO_2/MWh
Natural gas	56	0.2017
Mineral oil	77	0.2773
Coal	96	0.3457

Step 3: consists of modeling and inserting the equivalent renewables, which are the energetic effects of the new transmission projects, into the SDDP. In this specific case, two equivalent renewables were considered: a photovoltaic solar plant with installed capacity of 615 MW (+70 MW to be connected to bus **07**, +310 MW to be connected to bus **06**, +70 MW to be connected to bus **13**, +75 MW to be connected to bus **16**, and +90 MW to be connected to bus **14**) and a biomass thermal generation plant with an installed capacity of 261 MW (+140 MW to be connected to bus **11**, +91 MW to be connected to bus **13**, and +30 MW to be connected to bus **15**). Each of the plants could have been modeled individually, but since they are all in the same region, and to reduce the number of operations in the SDDP and consequently the chance of errors, the equivalent renewables were considered instead.

As previously mentioned, the assumptions and considerations related to the equivalent renewables directly impact the quality of the results. Hence, this modeling must be technically sound and based on real historical measurements whenever possible. So, the authors based the modeling of equivalent solar and equivalent biomass thermal on the historical generation data of plants in the region of interest from the Brazilian National System Operator's reports and dashboards [30]. Proportionality calculations were made between the installed

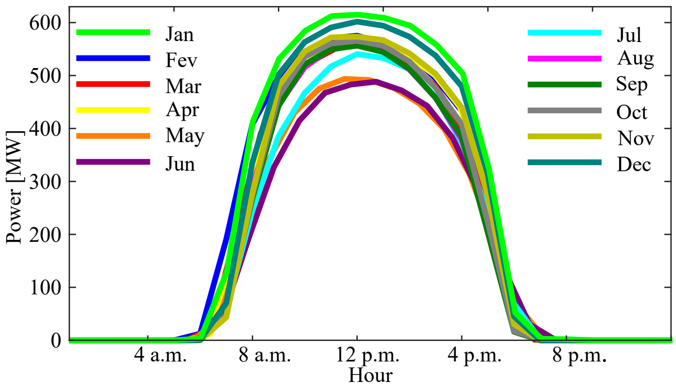

Fig. 4. Daily generation curves for the equivalent photovoltaic plant, with 615 MW of installed capacity. These curves were calculated from the historical generation data available in [30].

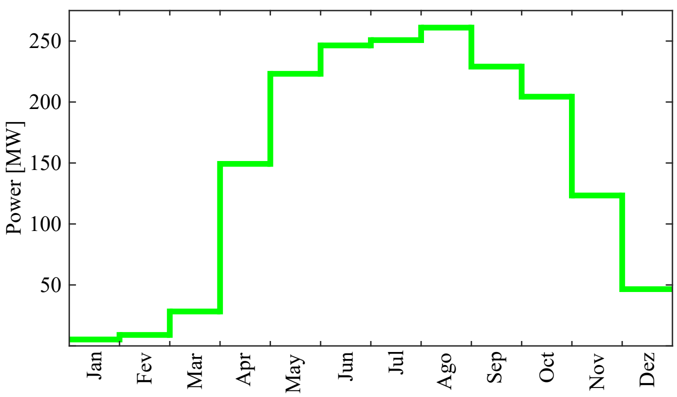

Fig. 5. Monthly generation of the equivalent biomass-based plant, with 261 MW of installed capacity, determined from the historical generation data available in [30].

capacities of the existing plants and the values of 615 MW for equivalent solar and 261 MW for equivalent biomass thermal. The equivalent solar plant was modeled considering that, on each day of the month, its hourly generation curve is always the same (the power of 615 MW is only reached on the days of January, around noon). Fig. 4, then, illustrates its daily generation curves. The sugarcane biomass thermal plant, in turn, was modeled considering that generation is constant throughout the day, but that the power generated on each month is different (generation is higher in the sugarcane harvest months, which runs from April to October, with August being the only month in which the plant generates 261 MW). Fig. 5 shows the generation in each month.

In the SDDP, the equivalent renewables were registered in the southeast subsystem (where the region of interest is). The equivalent biomass plant was registered as a zero-cost thermal plant with biomass fuel. According to [29], the CO_2 emission factor of sugarcane bagasse is zero since the carbon emitted during its combustion is the same carbon captured by the sugarcane during its growth. The equivalent solar plant, in turn, was also modeled as a zero-cost thermal plant, with fuel that does not emit CO_2 (sunlight), but with hourly generation. Then, with the equivalent renewables modeled and included in the SDDP, the authors proceeded to step **4**. Even so, it is worth noting that, in practice, hydro, solar, and, especially, biomass plants require operational and maintenance activities that entail some CO_2 emissions, e.g., biomass transport, processing, and storage; thermal machinery maintenance; and auxiliary services. This way, the zero emissions considered in the modeling are approximations, but reasonable ones, as the emissions from renewable sources are not significant compared to those of fossil-fuel-based thermal plants.

Step 4: in this step, the same operational policy for hydroelectric reservoirs and fossil fuel-based thermal power plants obtained in step **1** was simulated in the same 200 hydrological and renewable generation series of step **2** (to provide a fair comparison between emissions in each series in the final step), but, now, in the SDDP database that considers the generation of equivalent renewables. Once the simulation was completed, 1600 new emission values (also attributed entirely to the fossil thermal plants) were obtained. As in step **2**, the simulation of the 200 series in this step also took 16 minutes. Hence, please note that the total simulation time (steps **1**, **2**, and **4**) was approximately 6.5 hours (a result that may differ depending on the processor used, the database, the study horizon, etc.).

Step 5: then, in this step, the gross reductions in the CO_2 emissions were calculated through the differences between the emissions without and with the equivalent renewables.

Step 6: finally, in this step, the information provided by [19] and [20] was used to estimate the emissions associated with the construction of the new projects. Then, the net reductions were finally calculated by subtracting the emissions from the construction of the projects from the gross reductions obtained in the previous step. In this step, the authors also determined the time necessary for the transmission projects to compensate for the emissions of the construction-related stages.

IV. Results

Finally, this section presents the results. The results presented here are those of steps **2**, **4**, **5**, and **6**, which are of interest from the methodology's point of view (since the results of step **1** involve many files regarding the optimal operating policy of the reservoirs and those of step **3** comprise the entire massive volume of files that make up the original SDDP database [25] with the data of the equivalent renewables).

The 200 future series of hydrological and renewable generation parameters used in the policy simulations considering the system without (step **2**) and with (step **4**) the equivalent renewables were the same and these series were considered equally probable in this analysis of the results. These series include scenarios with low rainfall rates, in which conventional thermal plants are activated more often and emissions are higher; scenarios with an abundant rainfall regime, in which emissions are lower; and several intermediate scenarios. Yet, if of interest, different probabilities of occurrence for each series could be set.

Fig. 6 presents the annual CO_2 emissions of the whole Brazilian SIN for each of the 200 series, without the equivalent renewables (step **2**). Fig. 7, then, presents the SIN's emissions but considering the SDDP database with the equivalent renewables (step **4**). The data from these figures reveal that annual emissions vary significantly across hydrological series,

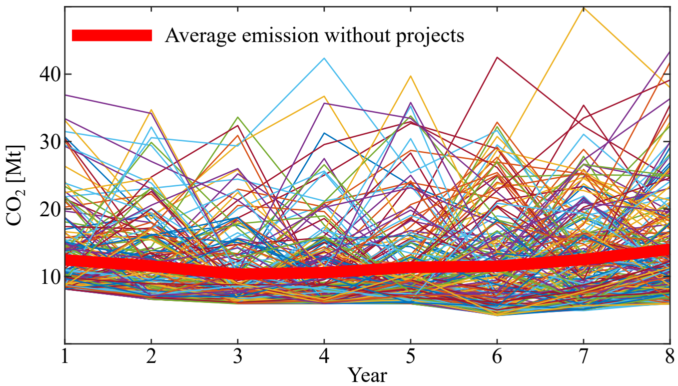

Fig. 6. CO_2 emissions (in millions of tons) of the SIN without the effect of the new transmission projects for each series (step **2**).

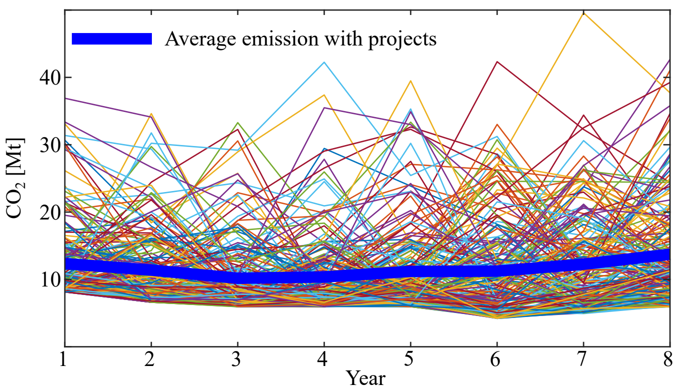

Fig. 7. CO_2 emissions (in millions of tons) of the SIN with the effect of the new transmission projects for each series (step **4**).

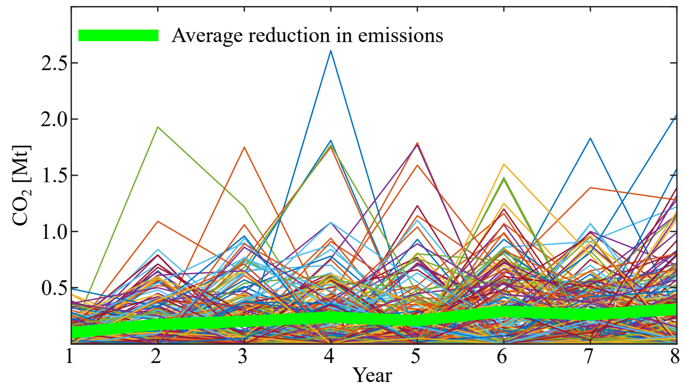

Fig. 8. Gross CO_2 emissions reductions (in millions of tons) due to the equivalent renewables for each series (step **5**).

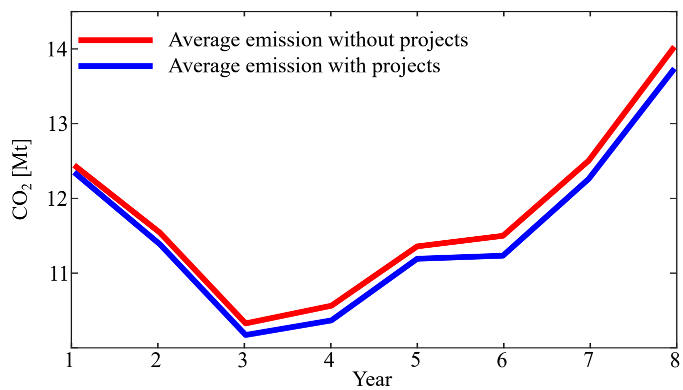

Fig. 9. Average annual CO_2 emissions curves, for cases without and with the effect of the new transmission projects (equivalent renewables).

reflecting the stochastic nature of the study, which analyzes 200 distinct series. In regions with higher rainfall, hydroelectric reservoirs have more water available, reducing the need for thermal power plants and, consequently, lowering CO_2 emissions. In contrast, series with lower rainfall rely more on thermal power plants, leading to increased emissions. This demonstrates that the simulations account for a wide range of scenarios. Therefore, it is valuable to calculate the average annual emissions. Additionally, it is important to note that, in terms of total system emissions, the reductions achieved by the projects analyzed are not substantial.

Fig. 8, then, presents the gross reduction in emissions; the differences between CO_2 emissions in year N, series i, without the effect of the projects, and emissions in year N, series i, with the effect of the projects, where i = $\{1, \cdots, 200\}$. As in Figs. 6 and 7, one can see that reductions in emissions vary significantly across hydrological series. This happens as in each series, the hydrothermal dispatch varies, as previously mentioned. In one specific series, please note that the total reductions in year 4 reached 2.5 million tons. However, since the case study presented here focuses on a relatively small portion of the SIN, these emission reductions are minor compared to the system's total emissions.

Fig. 9 shows only the annual average emissions of the cases with and without the equivalent renewables, and to complement the results, Table III presents the average (μ), cumulative average ($\Sigma\mu$), and maximum gross reductions verified for each year of the horizon. One can see that, starting in year 3, there is a clear trend: the average increases year after year. This may occur because, in most hydrological scenarios generated by the SDDP model from historical data, the model determined that the optimal hydro-thermal dispatch involves greater use of thermal generation from that year onward. Yet, this observation is specific to this study; that is, depending on the input data, the system under analysis, and the decisions made by the SDDP, the trend could be different.

The total gross average reduction in emissions due to the effect of new transmission projects in the region of interest in the eight-year future horizon considered in this case study was 1.775 million tons of CO_2, with a maximum of 5.980 million tons (sum of all the maximums per year). As previously mentioned, the reduction in emissions varies in each series because the hydrological and renewable generation conditions (parameters such as wind speeds and patterns, among others)

TABLE III
Gross Reductions in CO_2 Emissions per Year over the Future Horizon, in Millions of Tons

Year	1	2	3	4	5	6	7	8
μ	0.100	0.173	0.201	0.237	0.206	0.291	0.260	0.307
$\Sigma\mu$	0.100	0.273	0.474	0.711	0.917	1.208	1.468	1.775
max.	0.490	1.930	1.750	2.610	1.790	1.600	1.830	2.040

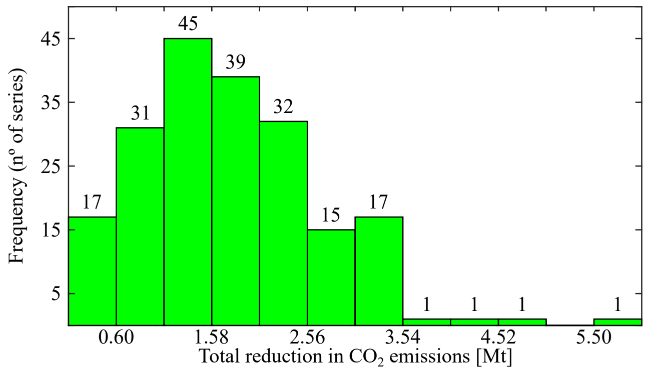

Fig. 10. Distribution of the total gross reductions in CO_2 emissions over the considered horizon, in millions of tons.

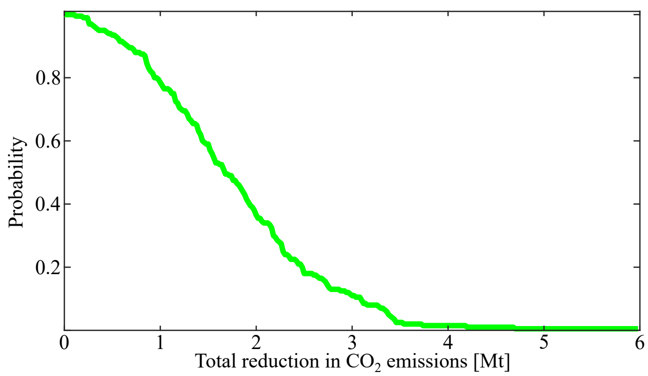

Fig. 11. Probability curve of the total gross reduction in emissions being greater than or equal to a certain value.

vary. In this regard, Fig. 10 presents the histogram of the distribution of the 200 results of gross emission reductions. One can clearly see that the gross reductions do not follow a normal distribution. Furthermore, one can observe that in more than half of the series (107), the total gross reductions exceeded 1.56 million tons, and that in 68 series, the total reductions exceeded 2.07 million tons. Still, it is worth noting that these results are a consequence of the operational decisions taken by the SDDP and will differ when considering historical hydrological series other than those used.

From Fig. 11, finally, one can calculate the probability of, in practice, the gross reductions in the first eight years being greater than or equal to a given value. For instance, the probabilities of the total gross reduction being $\geq$ to 1, 2, 3, and 4 million tons are 78.5%, 36.5%, 11%, and 1.5%.

The gross reduction results presented so far do not consider the CO_2 emissions from the projects' construction. Yet, calculating these emissions is not simple, especially if the precision required is high [19], [20]. Still, as previously mentioned, these emissions are also important and should be considered. In this case study, there were no available emission inventories related specifically to the considered projects. So, the results provided by [19] and [20] were used. Also, conservative assumptions were adopted, so the resulting emissions value is probably higher than those that are occurring and will occur in practice until the completion of the projects.

According to [19], the construction of a typical new 500 kV line causes emissions of 1642 tons of CO_2 per km. In this case study, the works on lines consider a new 440 kV line of 38 km and the reconstruction of 105 km of double-circuit 138 kV lines. Both the works on 440 and 138 kV lines should produce less emissions than constructing a new 500 kV line, but to maintain a conservative stance, it was considered that the emissions of each km of line linked to the projects in question equal $1642 \cdot 1.5 = 2463$ tons of CO_2 per km. The factor of +50% was included because the value of 1642 tons/km provided by [19] considers projects in China, but the projects considered here are in Brazil (the factor was freely adopted only due to the geographical difference between China and Brazil). Hence, the line works of the projects in question should not have CO_2 emissions more significant than $2463 \cdot 143 = 0.352$ million tons.

Reference [20], in turn, shows that the construction of a new substation in China with two new 220-110 kV and 240 MVA transformers each produces approximately 47250 tons of CO_2. The projects evaluated in the case study, in turn, consider two new transformers, one of 500-138 kV and 400 MVA and one of 440-138 kV and 300 MVA. To maintain the conservative estimate, the value of 47250 tons was then multiplied by (700)/(480) (MVA/MVA), (500/220) (kV/kV; the transformer with a 440 kV primary voltage was considered as 500 kV), (138/110) (kV/kV), and by 1.5 (the same conservative factor freely adopted for the lines, due to the geographic differences). Hence, the two new transformers should not have emissions greater than 0.295 million tons.

It is worth noting that in this study, which involves different renewable plants (five different photovoltaic solar plants and three different biomass plants, from different owners and built by different contractors and with the material from different suppliers), it was not possible to estimate the emissions associated with the construction of these plants. Still, please be informed that the conservative factors adopted to estimate emissions from the construction of the transmission infrastructure were also applied to account for emissions from the construction of the renewable plants. It is also important to note that while hydroelectric plants can have emissions close to zero during operation, as previously mentioned, they can still produce substantial GHGs emissions during construction, especially if they involve reservoirs. This is because forested areas are often flooded to create the reservoir and dam complex. These emissions are substantial and must be accurately accounted for when applying the methodology, particularly in cases where the renewable energy generated from the transmission expansion is hydroelectric with a reservoir. However, this is not applicable in the current case study.

This way, adding up the conservative estimates for the lines (0.352) and transformers (0.295) yields a total estimated emission of $0.352 + 0.295 = 0.647$ million tons of CO_2. So, the net reduction for the eight-year future horizon is $1.775 - 0.647 = 1.128$ million tons. Hence, please note the projects will need, on average, up to 4 years to offset the emissions from the infrastructure's construction, as the average gross reduction in the first four years is 0.711 million tons (Table III). As the useful life of these projects is at least 30 years, their future impact in terms of reducing emissions will indeed be significant.

The average net reduction of 1.128 million tons in eight years is due not only to the expansion of transmission but also to the renewable generations, which effectively replace fossil fuel-based generation, as mentioned. Still, the transmission expansions are those that allow the connection of the clean sources into the power grid. Hence, reductions are a joint effect of both new transmission and renewable generation, and this conclusion is in line with those of [4]- [16].

V. Discussion

A. Regarding the Case Study

In practice, delays in the construction of transmission projects may occur relative to the ideal schedule. In such cases, renewable generation could be constrained during the delays, and therefore, the emission reductions would be smaller. Still, the case study discussed has not considered this possibility; it assumed that, at the beginning of year 1, all transmission expansion projects had already been completed and that the new renewable generation could produce energy at its maximum capacity. This assumption was initially considered because the original transmission expansion planning study conducted by the EPE [28] does not report the increase in renewable generation that can be attributed to each new transmission reinforcement presented in the description of Fig. 3. To discover the individual energy effect of each new transmission project, several power flow simulations would be necessary, both in normal operation and contingency operation situations, and these are beyond the scope of this work.

Still, to illustrate how adverse a construction delay in some transmission projects can be from an emissions reduction standpoint, please consider that the reconstruction projects for the 138 kV double-circuit lines between buses **12** and **13** (normal/long-run capacities will increase from 139 to 249 MVA per circuit) and between buses **13** and **15** (normal/long-run capacities will increase from 80 to 139 MVA per circuit) are delayed by three years. In this context, it is reasonable to assume that the biomass plant with an installed capacity of 91 MW and the photovoltaic plant with an installed capacity of 70 MW on bus **13** could not generate all their available installed power, and that their generation would therefore be constrained to some fraction k of those installed capacities.

In just an investigative way, since the real value of the individual contribution of these transmission projects in terms of the amount of additional renewable generation that can be connected to bus **13** is not given in [28] and would need extensive simulations to determine, it could be somewhat credible that k could be the ratio of the total power output of bus **13** before and after the completion of the reconstruction projects, as in:

$$k = \frac{2 \cdot (139 + 80)}{2 \cdot (249 + 139)} = 0.564 \tag{1}$$

In this case, biomass generation would be constrained to $k \cdot 91 = 51.36$ MW and photovoltaic to $k \cdot 70 = 39.51$ MW in the first three years of the horizon. By redoing the simulation, a total average gross reduction of only 0.267 million tons of CO_2 was obtained (a reduction of 0.206 million tons compared to the 0.473 million tons that would be the gross reduction in emissions in the first three years of the horizon if there were no delay, reported in Table III). Even though the values of $k \cdot 91$ and $k \cdot 70$ MW are rough approximations, this sensitivity analysis shows that a delay in one or transmission project's completion can indeed be significant and adverse for the reduction in emissions. Anyway, please note that the methodology itself allows for the consideration of delays in the transmission expansion projects' completion.

In addition, please note that in the case study, the renewable plants were grouped because they are geographically and electrically close to each other, and to reduce the risk of modeling errors when modeling each one individually in the SDDP. However, this aggregation does not explicitly account for potential curtailment or locational constraints at shorter time scales. Hence, it may introduce bias, leading to emission reductions that, in practical situations where sporadic curtailment of an individual renewable plant (due to operational issues or severe contingencies in the transmission network), would be lower than those obtained when considering the grouping of individual plants into equivalent plants. Yet, it is worth commenting that the methodology does not necessarily require that individual renewable plants be aggregated, and that the decision to aggregate them was made in the specific context of the discussed case study.

B. Regarding the Methodology's Limitations

As mentioned earlier, the proposed methodology does not account for potential violations of the physical limits of the transmission network being analyzed. It relies exclusively on a simplified transport model that connects the regional subsystems. Consequently, in its current form, the methodology may oversimplify the intricate relationship between grid topology and the integration of renewable energy sources, particularly when the transmission expansion projects and new renewable generation plants spread across large areas.

Besides, please note that the methodology proposed in this research aims to demonstrate that transmission expansion projects designed to enable greater connectivity of renewable generation also contribute to emission reductions. Evidently, the reductions are a shared effect of transmission expansion and the additional renewable generation that this expansion of the electrical infrastructure allows to be connected, because while the additional renewable generation (in the case study, the +615 MW of solar photovoltaic generation and +261 MW of biomass thermal generation, which could not be connected at all if all transmission expansions are not implemented, according to [28]) effectively replaces fossil-fuel-based thermal generation, it is the transmission expansion that ensures that this generation is reliably accommodated. However, the methodology alone cannot determine which reductions are attributable to transmission expansion and new renewables individually. It attributes the reductions and environmental benefits to equal consequences of transmission expansion and renewable plants. Developing some more specific criteria for dividing emissions between renewable energy generators and the transmission utility, for example, based on economic parameters, to overcome this limitation of the methodology, could be the subject of future work.

VI. Conclusion

This paper reinforces and contributes to the discussion regarding the key role of transmission expansion in the transition towards sustainable development. It presents a novel methodology aimed at estimating, in a future horizon, the reductions in CO_2 emissions associated with new transmission projects that increase renewable energy generation capacity. This methodology also shows that even small transmission expansion endeavors, provided that they increase the capacity of renewable generation, can contribute significantly.

The application of the methodology in a case study consisting of new transmission projects in southeastern Brazil that will contribute to connecting +876 MW of renewable generation showed that, even accounting for the emissions from the construction stages, over a future horizon of eight years, the expansion of transmission will contribute to an average emission reduction of 1.128 million tons of CO_2 and that about 4 of the 30 years of projected lifespan for the whole "renewable plants + transmission expansion" project could be allocated to offsetting the construction-related emissions. Finally, it is also worth mentioning that future work may, for instance, expand this analysis to the financial study of the mentioned transmission expansion projects and aim to address the methodology's limitations.

References

[1] D. Gielen et al. The role of renewable energy in the global energy transformation, Energy Strategy Rev., vol. 24, pp. 38-50, Apr. 2019, DOI: 10.1016/j.esr.2019.01.006.

[2] F. Porrua et al. Incorporating large-scale renewable to the transmission grid: Technical and regulatory issues, 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 2009, pp. 1-7, DOI: 10.1109/PES.2009.5275657.

[3] X. Zeng et al. Highly-efficient single-level robust transmission expansion planning approach applicable to large-scale renewable energy integration, Sust. Energy Grids Netw., vol. 39, pp. 101486, Sep. 2024, DOI: 10.1016/j.segan.2024.101486.

[4] R. Golombek et al. The role of transmission and energy storage in European decarbonization towards 2050, Energy, vol. 239, pp. 122159, Jan. 2022, DOI: 10.1016/j.energy.2021.122159.

[5] J. Lotze et al. The complementary role of energy system and power grid models: An analysis of the European energy transformation from a holistic perspective, Energy Conv. Manag., vol. 315, pp. 118761, 2024, DOI: 10.1016/j.enconman.2024.118761.

[6] M. Mier et al. Collaboration, decarbonization, and distributional effects. Appl. Energy, vol. 341, pp. 121050, July 2023, DOI: 10.1016/j.apenergy.2023.121050.

[7] S. Karlsson et al. The roles of permitting times and grid expansion capacity in industrial decarbonization – A case study of the electrification of Swedish industry, Ener. Conv. Manag. X, vol. 26, pp. 100962, Apr. 2025, DOI: 10.1016/j.ecmx.2025.100962.

[8] H. Fell et al. Emissions, Transmission, and the Environmental Value of Renewable Energy, American Economic Journal: Economic Policy, vol. 13, no. 2, pp. 241-272, May 2021, DOI: 10.1257/pol.20190258.

[9] L. W. Davis et al. Transmission Impossible? Prospects for Decarbonizing the US Grid, Journal of Economic Perspectives, vol. 37, no. 4, pp. 155-180, Fall 2023, DOI: 10.1257/jep.37.4.155.

[10] S. Zapata et al. Investigating the concurrence of transmission grid expansion and the dissemination of renewables, Energy, vol. 276, pp. 127571, Aug. 2023, DOI: 10.1016/j.energy.2023.127571.

[11] A. Moreira et al. Reliable Renewable Generation and Transmission Expansion Planning: Co-Optimizing System's Resources for Meeting Renewable Targets, IEEE Trans. Power Syst., vol. 32, no. 4, pp. 3246-3257, July 2017, DOI: 10.1109/TPWRS.2016.2631450.

[12] R. Melo et al. Multi-year two-stage generation and transmission expansion planning: intermittent renewable energy sources integration for Brazilian interconnected power system, Electr. Eng., vol. 104, pp. 2689–2701, Feb. 2022, DOI: 10.1007/s00202-021-01456-6.

[13] C. A. Moraes et al. A probabilistic approach to assess the impact of wind power generation in transmission network expansion planning, Electr. Eng., vol. 104, pp. 1029–1040, July 2021, DOI: 10.1007/s00202-021-01361-y.

[14] H. C. Gils, S. Simon and R. Soria. 100% Renewable Energy Supply for Brazil—The Role of Sector Coupling and Regional Development, Energies, vol. 10, no. 11, pp. 1859, 2017, DOI: 10.3390/en10111859.

[15] W. Wang , Q. Tang and B. Gao. Exploration of CO_2 emission reduction pathways: identification of influencing factors of CO_2 emission and CO_2 emission reduction potential of power industry, Clean Technologies and Environmental Policy, vol. 25, pp. 1589–1603, 2023, DOI: 10.1016/j.jenvman.2022.114925.

[16] J. Xiao et al. Decarbonizing China's power sector by 2030 with consideration of technological progress and cross-regional power transmission, Energy Policy, vol. 150, pp. 112150, March 2021, DOI: 10.1016/j.enpol.2021.112150.

[17] T. J. Hammons et al. State of the Art in Ultrahigh-Voltage Transmission, Proceedings of the IEEE, vol. 100, no. 2, pp. 360-390, Feb. 2012, DOI: 10.1109/JPROC.2011.2152310.

[18] H. Wang et al. Transregional electricity transmission and carbon emissions: Evidence from ultra-high voltage transmission projects in China, Energy Economics, vol. 123, pp. 106751, July 2023, DOI: 10.1016/j.eneco.2023.106751.

[19] T. Liu et al. Carbon Emission Accounting during the Construction of Typical 500 kV Power Transmissions and Substations Using the Carbon Emission Factor Approach, Buildings, vol. 14, no. 1, pp. 145, Jan. 2024, DOI: 10.3390/buildings14010145.

[20] X. Chen and Y. Ou. Carbon emission accounting for power transmission and transformation equipment: An extended life cycle approach, Energy Reports, vol. 10, pp. 1369-1378, Nov. 2023, DOI: 10.1016/j.egyr.2023.08.010.

[21] M. V. Pereira and L. M. Pinto. Multi-stage stochastic optimization applied to energy planning, Math. Prog., vol. 52, pp. 359-375, 1991, DOI: 10.1007/BF01582895.

[22] J. Zhu et al. Spatiotemporal decomposed dispatch of integrated electricity-gas system via stochastic dual dynamic programming-based value function approximation, Energy, vol. 282, pp. 128247, Nov. 2023, DOI: 10.1016/j.energy.2023.128247.

[23] A. Helseth and B. Mo. Hydropower Aggregation by Spatial Decomposition—An SDDP Approach, IEEE Trans. Sust. Energy, vol. 14, no. 1, pp. 381-392, Jan. 2023, DOI: 10.1109/TSTE.2022.3214497.

[24] PSR. SDDP User Manual, available here, last accessed: Feb. 2026.

[25] Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia - Estudos de Apoio, available here, last accessed: Feb. 2026.

[26] Operador Nacional do Sistema. Sobre o SIN - O Sistema em Números, available here, last accessed: Feb. 2026.

[27] Empresa de Pesquisa Energética. Webmap EPE - Sistema de Informações Geográficas do Setor Energético Brasileiro, available here, last accessed: Feb. 2026.

[28] Empresa de Pesquisa Energética. Estudo Prospectivo para Escoamento do Potencial de Fotovoltaica/Biomassa na Região Noroeste do Estado de São Paulo, available here, last accessed: Feb. 2026.

[29] J. M. Coelho. A Bioeletricidade e o Planejamento Energético, VII Seminário Brasileiro de Bioeletricidade, 2017, available here.

[30] Operador Nacional do Sistema. Geração Média Diária e Horária, available here, last accessed: Feb. 2026.

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