

Computer Modeling for High-RES Systems: Exploring the Applicability of EnergyPLAN

Gabriel Fonseca Oliveira Roma
CeDRI, SusTEC
Instituto Politécnico de Bragança
Bragança, Portugal
Department of Electrical Engineering
Federal Technological University
of Paraná
Pato Branco, Brazil
gabrielroma@ipb.pt

Gérémi Gilson Dranka
Department of Electrical Engineering
Federal Technological University
of Paraná
geremidranka@utfpr.edu.br

Ângela Paula Ferreira
CeDRI, SusTEC
Instituto Politécnico de Bragança
Bragança, Portugal
apf@ipb.pt

Abstract—The global energy landscape is evolving, with distributed generation (DG) playing a key role. This study assesses the applicability of EnergyPLAN, a simulation tool, for a high renewable energy source (RES) system, focusing on Brazil. By comparing EnergyPLAN outputs with data from the Brazilian National System Operator (ONS), the research evaluates its accuracy. Findings show high accuracy in annual and monthly simulations for photovoltaic and hydroelectric plants but higher errors in daily simulations for variable RES like wind and solar. The study highlights the need for better modelling of variable RES and offers insights into EnergyPLAN's effectiveness for energy planning, contributing to more reliable energy systems.

Index Terms—Energy Planning, Energy Systems Computer Modeling, EnergyPLAN.

I. INTRODUCTION

The global energy landscape is undergoing swift expansion and transformation. Distributed generation (DG) plays a vital role in the modern energy landscape by producing electricity from numerous small sources located near the point of consumption [1]. This decentralized approach differs from traditional centralized power generation from large plants. While DG offers benefits such as improved efficiency and reduced transmission losses, it also introduces new challenges, such as grid integration issues and managing the variability of RES.

The variability and intermittency of RES present a significant challenge to the operation and planning of DG systems. Sources such as solar and wind power can exhibit limited predictability, occasionally leading to fluctuations in power supply and grid instability. The inability to utilize excess generation, a phenomenon known as curtailment, significantly hinders the optimization of distributed generation's advantages.

Careful design and implementation of energy plans empower stakeholders to mitigate grid instability, curtailment, and energy waste. Effective energy planning involves optimizing the energy source mix and accurately forecasting demand. This proactive approach improves grid reliability, minimizes energy losses, and ensures sustainable energy management for the future.

Advanced energy systems computer models play a vital role in predicting system variables and informing strategies for a more resilient future grid. These sophisticated models allow stakeholders to simulate scenarios, analyze parameters, and optimize energy systems for maximum efficiency and reliability [2]. Incorporating advanced computer models into energy planning processes is crucial for adapting to evolving energy needs and achieving a more sustainable and efficient energy infrastructure.

When it comes to energy planning tools and software, there is a diverse range of approaches available to address these challenges. Some tools utilize a bottom-up approach, focusing on detailed data and specific components to comprehensively understand the energy system. Others employ a top-down perspective, analyzing the overall system interactions and impacts to assess performance and identify potential improvements or optimizations at a higher level [3].

This study utilizes the EnergyPLAN software [4] as its primary tool, chosen for its user-friendly interface and widespread adoption in the modelling of energy systems in various countries, including Brazil [5]. EnergyPLAN operates as a bottom-up model, simulating energy systems across electricity, heat, and transport sectors.

While EnergyPLAN offers functionalities beyond electricity analysis, this research focuses exclusively on electrical aspects to streamline the analysis and explanation of electricity-related calculations.

The research aims to validate the computational model-

ing approach implemented in EnergyPLAN for the Brazilian power system in the year 2022 by comparing software-generated outputs with real data from the Brazilian National System Operator (ONS) website. In this way, this evaluation will assess EnergyPLAN’s outputs within the Brazilian energy system context.

The paper is organized as follows: Section 2 discusses computational modelling approaches and energy planning tools. Section 3 examines the theoretical framework and features of EnergyPLAN software. Section 4 outlines the methodology for a case study in the Brazilian electricity sector. Section 5 presents and discusses the simulation results compared with ONS data. Finally, Section 6 summarizes conclusions and future research directions.

II. COMPUTATIONAL MODELING APPROACHES IN ENERGY SYSTEMS

Two key approaches stand out in the computational modelling of energy systems: top-down and bottom-up models. Based on their distinct approaches, these models generate different results.

Top-down models primarily focus on the economy and future supply and demand analysis, considering factors such as economic growth, industrial output, and overall economic parameters. Top-down models utilize economic parameters and historical data to provide estimates, making them particularly valuable for short-term forecasting and decision-making rooted in economic trends. These models offer insights into the broader economic landscape, facilitating informed decisions based on prevailing market conditions [6].

On the other hand, bottom-up models prioritize detailed engineering methodologies and technological descriptions to estimate final generation and consumption. They delve into sector-specific intricacies, employing building physics and statistical methodologies to deliver a comprehensive and precise analysis. Unlike top-down models, which rely on economic parameters and historical data, bottom-up models offer optimistic estimates and operate independently of market behaviour, enhancing their predictive capabilities [7].

Computational models for energy systems can be broadly categorized into two main approaches: simulation-based and optimization-based tools. Simulation models aim to replicate the behaviour of existing energy systems under various scenarios by processing user-defined inputs such as energy demand and resource availability.

In contrast, optimization models focus on identifying the most efficient configuration for an energy system based on specified objectives. These models assist in determining the optimal mix of generation sources, storage capacity, and transmission infrastructure to achieve goals such as cost minimization or maximizing renewable energy integration [8].

Table 1 presents a selection of the most widely used tools for energy systems computer models, showcasing their diverse functionalities and main applications in energy systems modelling.

TABLE I.
OVERVIEW OF MOST USED ENERGY PLANNING TOOLS [9].

Tool	Developer	Model Type	Category
MARKAL	ETSAP/IEA	Bottom-up	Optimization
EnergyPLAN	Aalborg University	Bottom-up	Simulation
LEAP	Stockholm Environment	Top-down	Simulation
HOMER	NREL	Bottom-up	Optimization
MESSAGE	IIASA	Bottom-up	Optimization
OSeMOSYS	IIASA	Hybrid	Optimization
TIMES	IEA/ETSAP	Bottom-up	Optimization

Recent research has been dedicated to energy-environmental planning and the shift towards renewable energy-based systems. In their work, Sadri et al. [10] employed computer modelling tools such as the Grey model, artificial neural networks, and energy models, including LEAP and EnergyPLAN. Similarly, advancements in optimizing energy systems have been achieved through the integration of machine learning with EnergyPLAN. This approach significantly speeds up the optimization process while maintaining accuracy, demonstrating a 64% reduction in computational time compared to traditional methods [11].

The validation and review of the EnergyPLAN model have been crucial for the analysis of renewable-based energy systems, with a focus on sector integration and the utilization of variable RES. A comprehensive review of 315 articles that used the EnergyPLAN software emphasized its importance in addressing district heating, integrating RES, and promoting resource-efficient energy systems [12].

Dranka and Ferreira [5] explored the planning for a renewable future within the Brazilian power system, utilizing the EnergyPLAN model to evaluate future scenarios, including the realization of a 100% RES system in the country.

Furthermore, a systematic review of energy modeling tools emphasized their critical role in shaping sustainable energy solutions in developing regions, particularly Sub-Saharan Africa. This review highlighted the need for energy models that address unique regional challenges and integrate renewable energy sources effectively.

Furthermore, a systematic literature review of energy planning and modeling tools underscored their critical role in addressing energy challenges, particularly in Sub-Saharan Africa. This review pointed out that existing models often fail to capture the unique challenges of these regions, such as political instability and low electricity access, highlighting the need for models tailored to these specific contexts [13].

III. THEORETICAL FRAMEWORK

A. Mathematical Foundations of Energy System Modeling

Energy system computer modelling tools are often utilized without a comprehensive understanding of their internal mechanisms. These tools are commonly perceived as black boxes that operate by transforming inputs into outputs without transparently revealing the complex mathematical and logical

processes they employ. This section aims to investigate and elucidate the underlying mathematical and logical foundations of these tools, with the goal of uncovering the operational principles that govern their functionality.

Energy system modelling tools, including EnergyPLAN, typically begin by establishing a comprehensive picture of the energy system. This often involves analyzing electricity demand, E^D , values throughout the year, but may also encompass aspects like fuel supply, infrastructure capacities, and conversion technologies. Modelling tools conduct a thorough evaluation, starting with an overview of the annual demand and subsequently focusing on hourly analysis to make optimal decisions. This process can be mathematically expressed as:

$$E_{year}^D = \int_0^T D(t) dt \quad (1)$$

where, D represents the power demand at time t , and T signifies the total number of hours in a year.

The supply strategy outlines how the energy system computer model tools determine the electricity supply, E^S , for each hour, t , considering the concurrent demand, D , and the availability of resources, R , at that specific time. This strategy is encapsulated in the function, f , which maps the demand and resource availability to the supply. By improving this function, the tool ensures efficient allocation of electricity supply to meet the demand while adhering to constraints imposed by numerous factors, such as resource availability, technical and regulatory restrictions, among others, as depicted in the equation 2:

$$E^S(t) = f(D(t), R(t)) \quad (2)$$

The total energy supply E_{total}^S over a specified duration, typically a year, in an energy system is determined by the sum of electricity supplied by each energy source over time. This process ensures that all energy contributions from various sources are accounted for to meet the overall demand. Mathematically, the equation for E_{total}^S is expressed as:

$$E_{total}^S = \sum_{k=1}^{8760} \sum_i P_{ik}(t) \Delta t_k \quad (3)$$

The sum over k indicates summation over all 8760 hours of the year, i represents the available power sources, P_{ik} denotes the power supplied by source i at time k , t represents the variable time dependency. Δt_k signifies the time step, typically of one hour, in a specific hour k of the year. Equation 3 ensures that all energy contributions from various sources are accounted for to meet the overall demand. Each hour of the year is considered, and the energy supplied by each source at that hour is multiplied by the time step of one hour, summing up all contributions to determine the total energy supply over the year.

The energy systems computer models also rely on internal priorities to determine the allocation of energy generation from different sources. Figure 1 shows a flowchart of a generic algorithm to select internal priorities, which guides

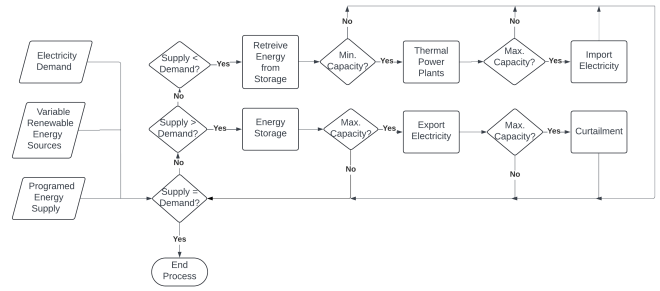


Fig. 1. Generic algorithm for selecting internal priorities in energy systems computer models.

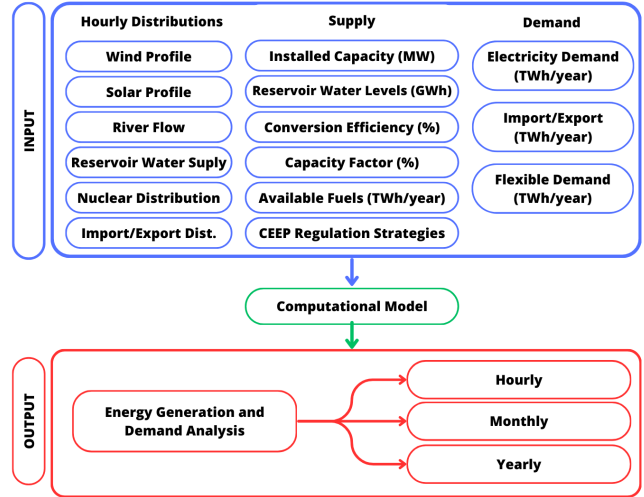


Fig. 2. Simplified block diagram of the EnergyPLAN electricity sector modeling.

the software to choose the most suitable energy sources based on predefined criteria and system limitations.

These priorities dictate the selection of energy sources based on factors like efficiency, cost-effectiveness, and environmental impact. Understanding these priorities is vital to effectively use software and make informed decisions regarding energy generation strategies.

B. Analysis of EnergyPLAN Electricity Mathematical Model

The EnergyPLAN software calculation process is elucidated through the comprehensive software documentation [4], which details the transformation of inputs into outputs. In order for the EnergyPLAN electricity model to function, it requires three key parameters: static values for installed capacity and electricity demand, the hourly distribution of the available resources and the load profile, and technical parameters such as capacity factor, power plant efficiency, and critical excess of electricity production (CEEP) strategies. Figure 2 shows a diagram that illustrates how these key parameters interact within EnergyPLAN.

When conducting its analysis, EnergyPLAN initially prioritizes the examination of the annual electricity demand. This evaluation hinges on two inputs: the total electricity

consumption within a year and the hourly distribution of energy demand throughout the year.

EnergyPLAN's electricity supply management is structured into two main sections: the Central Power Production module and the Variable Renewable Electricity module. The Central Power Production module handles thermal, nuclear, and hydroelectric power plants.

For thermal power plants, the model calculates the generated power based on the plant's capacity and operational hours. Similarly, for nuclear power plants, it considers the generator's capacity, a correction factor to adjust for variations between capacity and actual production, and the hourly distribution of electricity production throughout the year.

In hydroelectric power plants, EnergyPLAN calculates the average power production based on the annual water supply and the plant's efficiency. Operations are simulated hourly, and reservoir storage levels are managed according to water supply and demand.

In the Variable Renewable Electricity function, the focus is on installed capacity and the standardized distribution of resources such as wind speed, solar irradiation, or water flow for run-of-river power plants. Factors such as the height of the wind generation towers, the efficiency of the solar modules, and the efficiency of the hydro generators can significantly affect the capacity to generate electricity. The tool provides options for users to adjust these factors using correction procedures [4].

The model also requires the input of transmission line capacity to import and export energy. In cases of excess power production, excess electricity is exported within the transmission line's capacity. If insufficient, the model identifies a critical excess of power production (CEEP). EnergyPLAN includes features such as the CEEP regulation function, offering methods to address the issue, including curtailing renewable sources and using energy storage systems. During periods of insufficient power production, the model automatically initiates electricity imports.

IV. CASE STUDY

Brazil presents a compelling case study for investigating the applicability of computational modelling tools, such as EnergyPLAN, in validating complex power systems. The country boasts a leading position in integrating renewable energy sources (RES) into its national grid. With a significant portion of its electricity generation coming from hydropower, wind, and solar, Brazil offers a real-world example of a system heavily reliant on variable renewable sources [14]. This characteristic makes it an ideal test-bed for evaluating EnergyPLAN's effectiveness in simulating the behaviour of such systems. In addition, Brazil's vast geographical expanse presents unique challenges for grid management. The country's continental size necessitates long-distance transmission lines and necessitates consideration of diverse regional energy profiles.

The transparent data provided by the National System Operator (ONS) of Brazil has been instrumental in enhancing

the research process. ONS databases offer detailed information on hourly load curves, reservoir water levels, installed capacity breakdown by energy sources, and specific data on wind and photovoltaic power.

This rigorous approach not only validated the existing data but also provided valuable insights that complemented the research beyond what was available through the ONS resources alone. The analysis was conducted for the year 2022.

A. Electricity Demand and Transmission Line

The ONS database provided data for electricity demand analysis. The data set includes the hourly load distribution curve and the annual electricity demand. In addition, the data available also provides information for the input of fixed external requests for the import/export of electricity. However, since these requests represent less than 0.0001% of the total electricity demand, they were excluded from the model.

B. Thermal and Nuclear Power Plants

Thermal and nuclear power plant data on installed capacity were sourced from the ONS installed capacity database. An inherent challenge encountered by all energy generation sources is the fluctuation in installed capacity over the course of a year. The software currently utilized does not account for this variability; instead, it relies on a static value for the duration. To mitigate this issue, the input value in the computational tool reflects the average installed capacity of the respective energy sources incorporated into the model.

Although both thermal and nuclear power plants are modelled in EnergyPLAN, the inclusion of hourly distribution becomes crucial for nuclear facilities. Due to the limited accessibility and unpredictability of data for nuclear power plants, the hourly distribution for nuclear power was determined based on its energy production in 2022.

C. Hydroelectric Power Plants

In the context of the Brazilian power system, categorizing hydroelectricity production into reservoir and run-of-the-river hydropower plants presents challenges. Many hydroelectric power plants in Brazil operate as a hybrid of both types, utilizing reservoirs for storage water power generation while also functioning as run-of-the-river facilities [5]. Complicating this classification further is the fact that the ONS database combines data on installed capacity and electricity production for both types of plants under a single category: hydroelectric energy. To address this issue, an extensive review of the literature, official databases, and scientific articles was conducted to accurately allocate installed capacity and energy generation between these two configurations.

In the previous model of the Brazilian power system, it was reported that 46% of the installed capacity was attributed to reservoir hydropower plants, while run-of-the-river power plants accounted for 54% [5]. However, the Ten-Year Energy Expansion Plan of 2023 (PDE) [15] highlights a significant disparity over the past decade. Specifically, there has been a mere 2% increase in reservoir storage capacity compared to

a substantial 36% increase in the installed capacity of run-of-the-river hydroelectric power plants.

Analysis from the schematic diagram of Hydroelectric Power Plants within the Interlinked National System (SIN) reveals that 40.5% of the installed capacity is attributed to reservoir hydropower plants, while the remaining 59.5% is derived from run-of-the-river power plants, which are the figures utilized in this research [16].

The analysis of run-of-the-river electricity generation in the EnergyPLAN model involved combining the river flow data from specific basin pairs. The combinations were made by calculating a weighted average based on the installed capacities of each basin within the following pairs: Paraná-Uruguay, Amazon-Tocantins and East Atlantic-São-Francisco. Furthermore, the selection of basins for this analysis took into account the geographic proximity between them, ensuring a more realistic representation of the combined river flow. This methodology was implemented to work within the limitations of the EnergyPLAN software, which has a restricted number of inputs available.

Regarding reservoir hydropower plants, the model allows for the input of a single water flow distribution. The selected distribution was a weighted average of the combined basins mentioned before: Paraná-Uruguay, Amazon-Tocantins, and East Atlantic-São Francisco [16].

D. Wind and Solar Power Plants

Most of the wind energy generation in Brazil is concentrated in the Northeast region, which represents 90% of the national wind energy production. Within this region, three states dominate production: Bahia (31%), Rio Grande do Norte (29.5%), and Piauí (14%).

Hourly distribution data were obtained from the Renewables.ninja platform, which provides high-resolution renewable energy data worldwide, including crucial parameters such as wind speed and capacity factors [17] [18].

To represent the model, geographical locations corresponding to the largest wind farms in the aforementioned states were selected: the Laranjeira complex in Bahia, the Lagoa dos Ventos complex in Piauí, and the Rio dos Ventos complex in Rio Grande do Norte [19]. The installed capacity in each region was allocated proportionally according to the share of energy production.

Photovoltaic modelling followed a similar methodology, with three states - Bahia (25.3%), Piauí (20.4%), and Minas Gerais (18.7%) - contributing approximately two-thirds of the total energy generation. The hourly distribution of solar irradiation data was obtained using the PVGIS platform [20]. Developed by the European Commission's Joint Research Centre (JRC), PVGIS is an online tool that offers valuable insights into the solar energy potential of various regions worldwide.

The PVGIS tool was utilized to input the locations of the largest photovoltaic power plants in each state: Conjunto Solar do Sertão in Bahia, Conjunto São Gonçalo in Piauí, and Conjunto Pirapora in Minas Gerais [19]. The distribution of

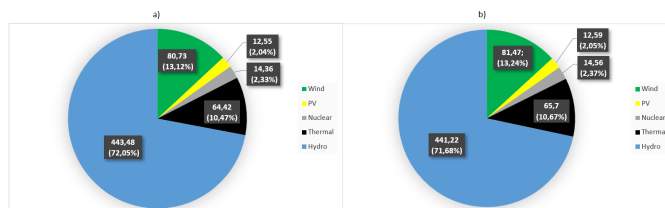


Fig. 3. Comparison of energy generation in TWh/year and percentage difference: a) EnergyPLAN outputs vs. b) ONS data (year 2022).

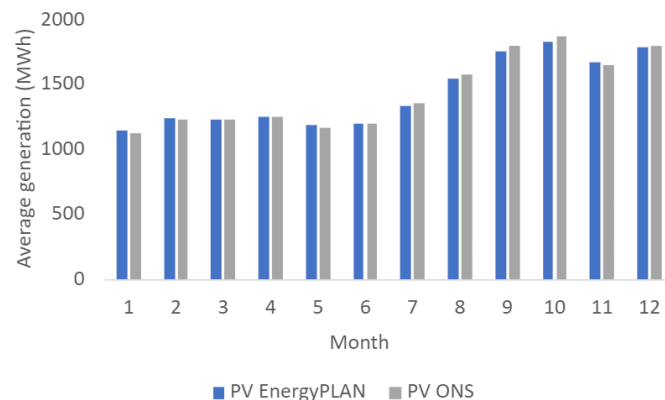


Fig. 4. Monthly comparison of photovoltaic generation between ONS data and EnergyPLAN simulations (year 2022).

installed capacity in these regions was proportional to their respective share of energy production.

V. RESULTS AND DISCUSSION

A. Annual Results

The research findings reveal a high level of accuracy in the annual energy generation analysis, with minimal errors detected. The results of the software simulation closely match the data from the ONS history of operation. Figure 3 illustrates the simulated values compared to the empirical data obtained from the ONS in percentage and in TWh/year.

From the data output above, the maximum percentage error for the thermal power plant did not exceed 2%. Furthermore, the deviation for the hydroelectric power plant, which accounts for more than 70% of the total annual energy production, was only 0.56%.

B. Monthly Results

In the context of monthly power generation, the accuracy of the results for both photovoltaic and hydroelectric power plants was notably high, attributed to the consistent availability of solar irradiation and water flow resources on a monthly basis. Despite the potential daily fluctuations in solar irradiation, these values exhibit remarkable stability over the course of a month. Figure 4 depicts the simulated and real output of photovoltaic generation for each month of the year, while Figure 5 illustrates the corresponding data for hydropower generation.

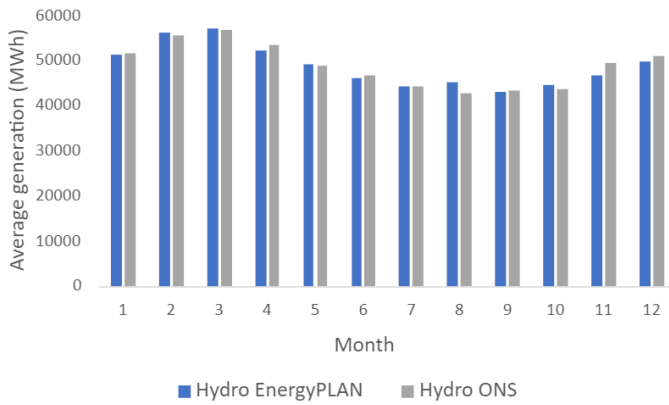


Fig. 5. Monthly comparison of hydropower generation between ONS data and EnergyPLAN simulations (year 2022)

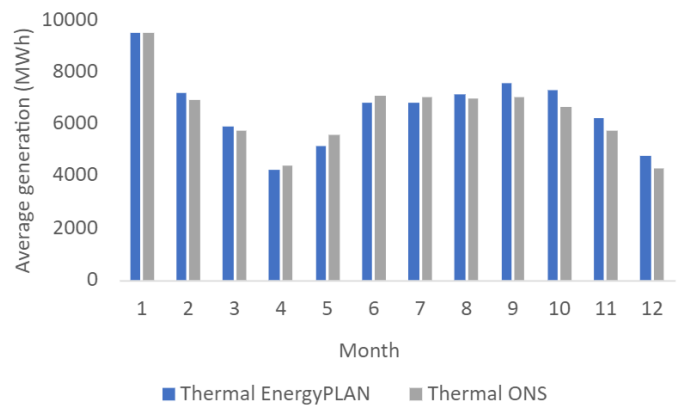


Fig. 7. Monthly comparison of thermal power generation between ONS data and EnergyPLAN simulations (year 2022)

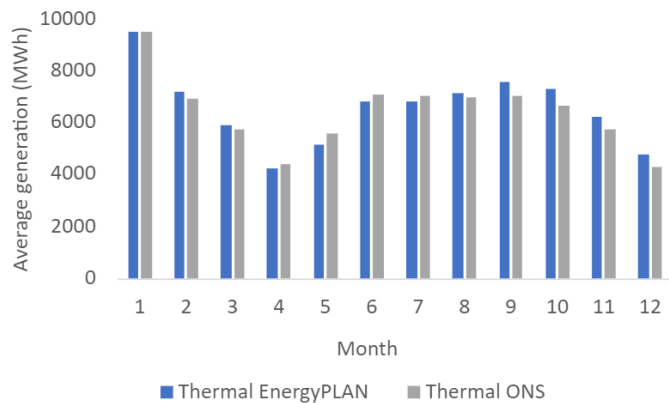


Fig. 6. Monthly comparison of wind power generation between ONS data and EnergyPLAN simulations (year 2022).

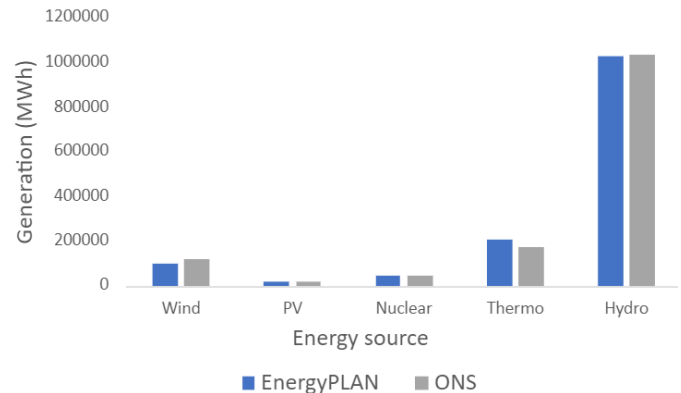


Fig. 8. Comparison of daily generation data between EnergyPLAN simulation and ONS data for summer.

However, wind and thermal power plants showed a higher error margin compared to photovoltaic and hydroelectric power plants. A comparison between the EnergyPLAN and ONS generation values for wind power plants is displayed in Figure 6, while Figure 7 presents the corresponding data for thermal power plants.

In regard to wind power plants, the error can be attributed to simplifications in the hourly distribution of wind speed. Despite the numerous wind power plants across Brazil and the variety of generators, the EnergyPLAN model uses a limited dataset, focusing on the three largest power plants in high-capacity regions.

With respect to thermal power plants, the operation of the computational model is a key factor in the observed discrepancies. In EnergyPLAN, thermal power plants are a last resort and only generate power to meet demand shortfalls after exhausting other energy sources. This explains why, in the case of insufficient generation of electricity from alternative sources, the thermal power plant compensates for the differences by adjusting its output, as shown in Figures 6 and 7.

C. Daily Results

From the daily-basis analysis, Figures 8 and 9 illustrate the daily generation data from the EnergyPLAN output and the actual data from the ONS for a random day in summer and winter, respectively. The obtained error is significantly more pronounced, primarily due to the variability and intermittency of renewable energy sources. These sources exhibit fluctuating daily values, heavily influenced by weather conditions on any given day.

Despite the discrepancies observed in both seasons, such outcomes are anticipated, given the dependency of energy sources on climatic conditions, which can vary considerably on a daily basis. This underscores the difficulties associated with long-term energy planning on a daily basis.

VI. CONCLUSION

The analysis of the EnergyPLAN software outputs in comparison to real-world data from the ONS on different time scales reveals valuable insights into the accuracy and reliability of the simulation results. The annual analysis demonstrates a high level of precision, with minimal errors detected and a close alignment between the simulated and empirical data.

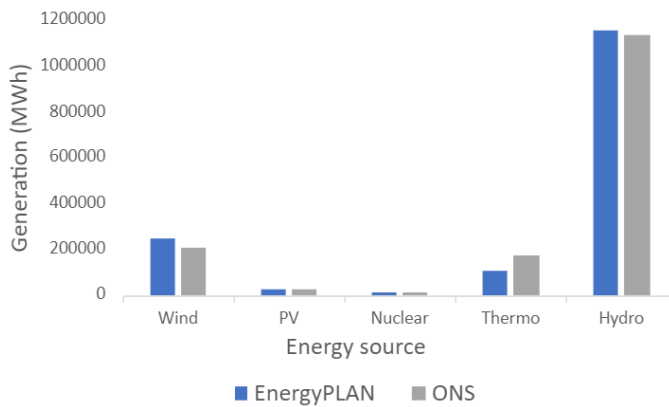


Fig. 9. Comparison of daily generation data between EnergyPLAN simulation and ONS data for winter.

This suggests that EnergyPLAN is effective in capturing long-term energy generation patterns and trends.

On a monthly basis, the results vary across different types of power plants. Photovoltaic and hydroelectric plants exhibit notable accuracy, attributed to consistent resource availability. In contrast, wind and thermal power plants show higher error margins, emphasizing the challenges in modelling sources with variable generation patterns. These discrepancies highlight the need for further refinement in modelling approaches to enhance the accuracy of monthly energy generation simulations.

When analyzing daily energy generation, significant errors become more pronounced because of the inherent variability and intermittency of renewable energy sources influenced by daily weather conditions. The comparison between EnergyPLAN simulations and ONS data for random days in summer and winter showcases the difficulties in accurately predicting daily energy generation.

Despite the observed discrepancies in monthly and daily analyses, this study's successful validation of the EnergyPLAN model highlights the importance of thoroughly analyzing all processes and calculations within an energy system computer model. Validating an existing model not only confirms its reliability but also provides valuable insights into its operations.

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