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Power System Modeling for the Study of High Penetration of Distributed Photovoltaic Energy

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Abstract: Many conventional power systems are evolving due to the growth of renewable energy and distributed energy resources (DERs). Modeling the interplay of transmission and distribution systems is critical to analyze how DERs impact a system's conventional operation and which electric infrastructure improvements are needed to achieve a balance between centralized generation and DERs. This article describes the process, tools, and resources used to model electric power systems with a centralized infrastructure in an isolated context and limited access to actual utility data. Photovoltaic systems installed on residential rooftops were the main design option. This work broadened the typical power system modeling to include planning and social considerations. This integrative engineering-social method allows for interdisciplinary teams to work in the development of a model as part of broader design goals for a renewable-dominant energy system. The Puerto Rico electric power system was used as a case study to demonstrate the process. The integrative engineering-social perspective in developing the model and the actions to manage data limitations are aspects that could be followed in other locations with aggressive renewable energy goals and where utility data are not readily available.

Keywords: photovoltaic systems; distributed energy resources; sustainable energy; power system modeling

1. Introduction

Technological advances and environmental concerns are causing dramatic changes in electrical systems worldwide. Electric utilities are planning the way forward to face electric industry challenges. This planning process will impact future investments in new infrastructure, operation, and maintenance. The challenges of energy transitions, e.g., going from a dominant electric power arrangement to another, go beyond engineering to energy policy, and socio-economic planning. In many instances, it is not enough to inform policy makers about technological options, engineers should get involved in agenda setting and policy analysis to ensure a broader impact on society [1]. The key role of this paradigmatic shift and the importance of collaborations among engineers and social scientists are shown on locations that have aggressive renewable energy goals that require a strong social agreement to achieve them [2,3]. For example, renewable energy and in particular distributed energy resources (DER), present both sustainability and resilience benefits to tropical and subtropical regions in the world that are vulnerable to natural disasters such as hurricanes and earthquakes. The conventional, hierarchical power structure could be complemented by local DERs and eventually, centralized power could be refocused to support the use of local resources [4]. This technological transformation of the electric power infrastructure might make sense from the engineering perspective, but it must also fully address social needs to ensure the benefits reach all segments of society. Even the best idea can fail when technology is incompatible with the social context [4]. Thus, there is a need to prove the feasibility of integrating more renewable energy into the grid, especially in low-inertia

systems such as those in islanded or remote locations and including both technical and social considerations.

This paper describes the process, tools, and resources used to model power systems in a low-inertia, isolated, or remote context, with limited access to actual system data from utilities. This paper strives to broaden the typical power system modeling to include planning and social considerations. Although utility planning divisions take a similar approach, the social data are usually obtained from a government or entity outside the utility, with little or no interactions between utility personnel and social planners. The method followed on this paper allows for interdisciplinary teams to work in the development of a model as part of broader design goals for a renewable-dominant energy system [3]. Social data were used as input to create a power system model, resulting in a more realistic and useful tool. Puerto Rico's existing electric power system was used as a simulation case study to illustrate the process. The case study used quasi-steady-state modeling for long-term studies as an initial approach. In addition to the limited utility data, information directly related to electrical components was used to describe the transmission, sub-transmission, and distribution systems and the demand distribution and profile of the archipelago. Furthermore, the limited land availability in small islands is one of the main concerns about the transition from traditional generation to renewable energy [5]. For that reason, the potential electricity production by PV systems installed on residential rooftops was evaluated and calculated for the Puerto Rican case. Finally, the distributed PV (DPV) integration modeling is explained as a key element in future research to study possible scenarios of different levels of PV-based DERs penetration and in support of new, more distributed power grid designs that are renewable-based.

Accessing utility data was a key challenge in this work. The lack of actual data from utilities is a common roadblock for power systems researchers [6]. Researchers used the latest data available at the time of the study (2017–2019) and were able to validate the accuracy of the model in spite of this data limitation. Thus, the integrative engineering-social perspective in developing the model and the actions to manage data limitations are aspects that could be followed by others seeking a more holistic view of power infrastructure analysis. The process followed in this work could also guide future research requiring modeling existing power systems under similar conditions and analyzing DER impacts (especially PV systems) on grid operation. The model will be used in the future by engineers and social scientists in crafting and analyzing plausible scenarios of renewable energy integration in a low-inertia power system.

1.1. Hybrid Transmission-Distribution System Modeling

Diverse computational tools are used to facilitate the analysis of existing and potential future scenarios in complex systems without interfering in regular operations. It is crucial to get accurate parameters for power system components to reduce simulation uncertainty and model the system elements' interaction in a precise way. The study and analysis of electric power systems can be approached at different time scales depending on the study focus [7]. The type of study determines the modeling used to represent the electrical components under analysis. Lightning propagation and switching transient studies require time steps on the order of microseconds (10^{-6} s). In contrast, power flow studies and unit commitment problems can be solved using time steps on the order of hours and days (see Figure 1).
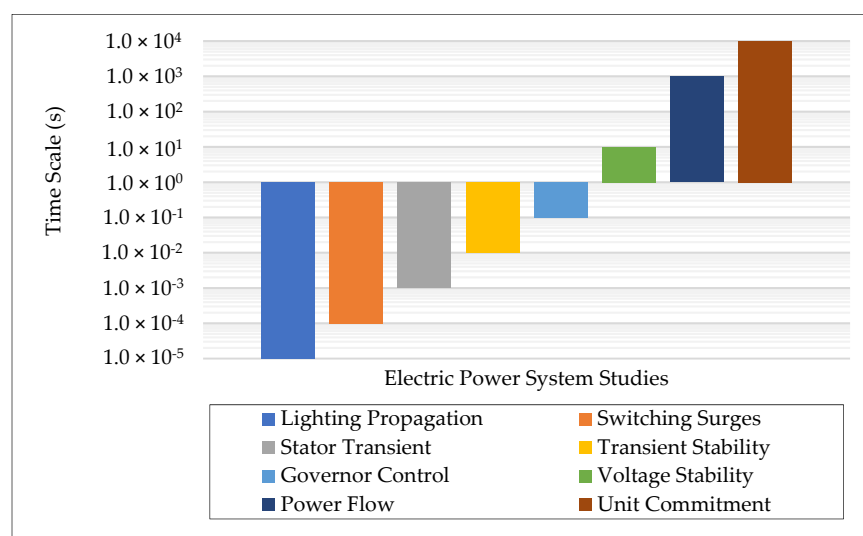
Figure 1. Time scales for electric power system studies (Based on [7]).

Traditional approaches suggest studying transmission and distribution systems separately. However, studying the transmission-distribution interplay is vital to achieve a balance between the large-scale transmission network and the smaller scale distribution systems with a high penetration of renewables. Modeling the interplay of transmission and distribution systems is critical to analyze how DERs impact a system's conventional operation. Similarly, considering this interplay contributes to answering questions about the effectiveness of transmission systems' controls in addressing operational challenges at DERs levels [8]. Finally, more complete models are required to investigate the dynamic interactions between the electric power transmission and distribution systems due to the continuous deployment of distributed energy resources (DERs). Nevertheless, modeling the equivalent dynamic behavior of aggregated loads and DERs, representing the entire distribution network, is a complex and computationally demanding task [9].

There is a great interest in studying the interplay between transmission and distribution systems [8–11]. To model large distribution systems, utilities use an aggregated representation of all the equipment connected to a distribution feeder to optimize computational operations in electrical studies. This simplification is made assuming that the consumption profile of users along the feeder is similar. However, customers' behavior is aimed at totally or partially generating their own electricity. For that reason, engineers are looking for ways to simplify the grid topology while keeping realistic models, using more accurate criteria.

Loads can be classified according to their behavior during a disturbance. Distribution networks that actively participate in system dynamics through load responses during disturbances are called "active". The distribution networks without activity are called "latent" [10]. This approach enables a detailed dynamic simulation for both transmission and distribution systems. After completing the first iteration of the disturbance on the study, a network could be immediately declared as "latent" and modeled in a simplified way or could be considered as "active" and modeled in detail. Studies suggest that the level of activity in a distribution feeder could be quantified and then classified through their apparent power variation.

Another way to model distribution networks for hybrid transmission-distribution system modeling is based on social and economic information by areas [12]. According to the collected data, distribution networks are classified by type of load (residential, industrial, agricultural, and tertiary consumers). This type of classification strives to reduce the detailed models and, in a way, to aggregate distribution networks with similar socioeconomic characteristics to the transmission system. As a result, reduced models of distribution feeders are used, decreasing complexity and computational time in simulations.

On the other hand, there are efforts to model the complete combined transmission and distribution system using new software or even several software tools working at the same time. Authors in [9] developed a co-simulation platform: the Integrated Grid Modeling System at the National Renewable Energy Laboratory (NREL). Transmission level operations (economic dispatch and unit commitment) are simulated with FESTIV software. This software is coupled with MATPOWER, which calculates a balanced positive-sequence AC power flow for the transmission system. The power flow solution obtained in MATPOWER is used as input for distribution feeders modeled with GribLAB-D, which finally runs a three-phase unbalanced AC power flow at the distribution level.

In comparison with the latter approach, a three-phase dynamics analyzer was developed to study steady-state and dynamic responses of power systems, using an unbalanced three-phase model [11]. This study used the IEEE 39-Bus system as the transmission system and the IEEE 123-Bus as the distribution system. Besides, the authors simulated the hybrid model as one large power system using the Distributed Engineering Workstation software [11]. The distribution and transmission systems were modeled separately and then compared to the integrated transmission and distribution system model. As a result, the authors highlighted the need to simulate combined transmission and distribution systems for planning and operation studies.

In general, there is a trend towards the unbalanced three-phase model, which is closer to physical system behavior [8]. However, given the complexity of unbalanced-network hybrid simulation due to a large number of elements to be considered, simplifying assumptions should be made to facilitate the problem. Furthermore, there is not a study that includes the impacts of DPV systems connected at the distribution level on an island-type electric system and considers the response of conventional generators to encourage an increased level of PV integration.

1.2. PV Modeling and Implications for Bulk Power System Simulations

To study the PV integration impacts on the power system, it is necessary to consider the type of study that will be carried out. Transmission systems planning studies generally focus on what is the system behavior after a contingency. In this sense, positive-sequence models are currently used to perform power flow calculations and dynamics studies. Besides, aggregated models of PV are recommended by the Western Electricity Coordinating Council and others for power system studies [13,14]. A PV-aggregated model allows controlling both active and reactive power output. The PV energy output in the aggregated model strictly depends on PV parameters and the irradiance and temperature forecasting for the PV location. Furthermore, there are no totally accepted, aggregated dynamic models for small-scale PV systems [15].

To study the impact of DPV systems on bulk power systems (BPS), references [16,17] suggest simulating the whole electric system: transmission lines, transformers, sub-transmission lines (in some cases), and distribution system. Differences between integrated simulations (transmission and distribution systems) and separate simulations were observed in [16]. It was concluded that a sudden change in PV output could impact another distribution network through the transmission network. This fact could cause a cascading disconnection of DPV systems, affecting the whole system's stability.

Different considerations need to be considered to approach the problem of the PV system modeling in BPS.

(1)   General considerations:

There is a trend towards multi-phase models because they consider the unbalanced nature of the distribution system [15]. Three-phase simulations were used in [14,18], although there is a difference in the way they modeled PV settings. While [14] modeled PV as active power sources, [18] added the voltage regulation offered by PV systems. Even though modeling BPS with a multi-phase representation of DERs and distribution feeders is essential for accurate studies, modeling hundreds or thousands of DPV systems in detail

is a complex task, as discussed earlier. For this reason, it is important to look for ways of simplifying the PV connection at the distribution voltage level using aggregated models.

(2)   Aggregated models:

PV integration can be simplified using different methodologies. On the one hand, PV systems could be simplified by (1) a model aggregation (i.e., clustering of models with similar performance), (2) derivation of equivalent models (i.e., reduced-order representation), or (3) a combination of the two [19]. On the other hand, research suggests a more systemic clustering methodology to group smart inverters connected to secondary systems. For example, a cluster could be formed considering the PV connectivity strength (the number of buses between them) [20]. Furthermore, the netting of DERs with loads at the transmission or medium-voltage bus is not a suitable way to simplify the PV modeling for high-DER penetration scenarios. In contrast, the resulting models misrepresent potential aggregated impacts of DERs on BPS [13,19].

(3)   Geographical distribution:

The smoothing effects of DPV systems are considered in [6,17]. Through spatial-temporal analysis performed for Puerto Rico in [6], the variability of PV output was studied. Results showed that the variability decreased at lower time scales when PV systems are dispersed around the system. These studies showed that if PV systems are geographically distributed in distribution systems, a reduction in output fluctuations is achieved. Thus, through the optimal allocation of PV, sudden changes in PV output are minimized as well as the negative impacts at the transmission level.

To study the interplay between transmission and distribution systems with a high level of PV-based DERs, it is essential to account for the distinctive and relevant features of PV systems when creating DER models. PV allocation and the proximity between PV systems are key to determine the impacts on the electric grid [21]. Also, individual PV output in distribution systems is not equal to aggregated PV output connected to a transmission bus, since the geographic distribution of PV smooths the output fluctuations [17] as already mentioned. Finally, increasing PV penetration at the distribution level could reduce transmission line strain due to the direct injection of energy near the load centers. Nevertheless, the lack of PV dynamic disturbance ride-through capability and the displacement of conventional generation by DERs could negatively affect the operation safety requirements of the entire system [22].

1.3. The Electric Infrastructure in Puerto Rico

Puerto Rico has been struggling with its electric infrastructure at least for the last 15 years. A reduced industrial demand caused by the exodus of many industrial clients and decades of short-sighted management, created financial instability in Puerto Rico's sole utility. Direct consequences of the financial problems were: reduced maintenance and an inability of keeping pace with technological advances [23]. Natural disasters, such as hurricane María in 2017 and earthquakes in early 2020 showed the frailty of the local power system and the need to re-think the electric infrastructure [24]. On the other hand, since the 1990s diverse stakeholders called for an increased use of renewable energy and more recently, distributed energy resources [3]. However, even with the dire financial and infrastructure conditions, the utility did not seek assistance in re-designing the grid and insisted on the centralized design that was proven ineffective by hurricane María and the 2020 earthquakes. This lack of collaboration has led some stakeholders to produce models based on publicly-available data in support of new, more distributed, and renewable-based power grid designs.

At the time of this study, the Puerto Rico Electric Power Authority (PREPA), a government-owned corporation, produced 70% of all electric energy and transmitted and distributed it in the archipelago. On June 2021, the operation, transmission and distribution were assigned to LUMA, a private consortium. Puerto Rico's power system backbone is the 230 and 115 kV transmission network, whereas a 38 kV system, which is

considered sub-transmission, works as a link between the transmission system and about two-thirds of the distribution substations and most private substations on the island [25]. Finally, the distribution system serves most customers at 13.2, 8.32, and 4.16 kV, with a small portion at 7.2 kV.

2. Methodology

In order to evaluate the impacts of DERs on an existing electrical grid, an exhaustive study about the main electrical components of the actual power system is required. Figure 2 illustrates the process followed to study and create the model, including available conventional generators, existing transmission and distribution lines, transformers, and electricity use patterns. The subsections describe information, sources, and calculations used to simulate and validate the Puerto Rico power system as realistically as possible. Moreover, the procedure to estimate potential electricity production by residential rooftop PV systems and the process to analyze irradiance conditions for sunny and cloudy days are described. This methodology could be replicated in other remote or islanded contexts to evaluate potential scenarios for the power grid, identifying the optimal penetration level and allocation of renewable systems and the grid upgrades required to support the highest possible integration of renewable energy.
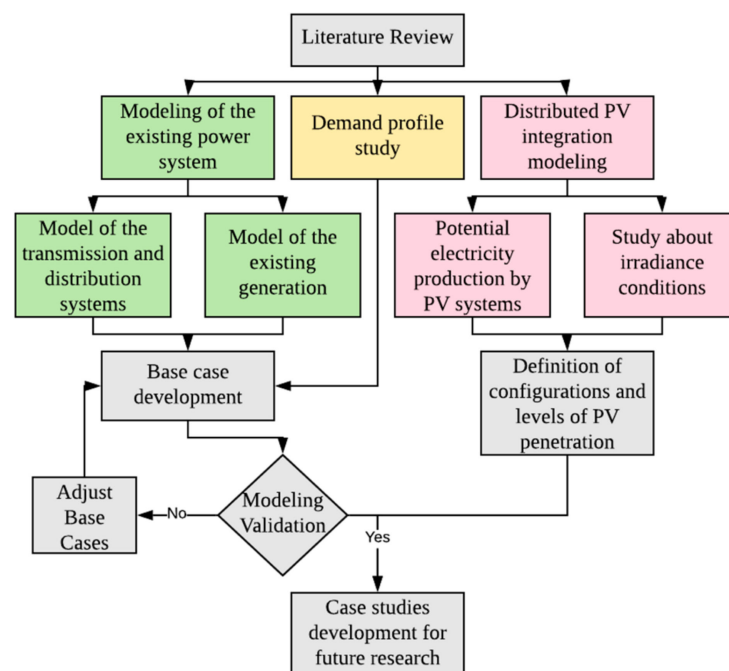

Figure 2. Steps for modeling and evaluation of isolated electric power systems with potential electricity production from PV-based DERs.

DIgSILENT PowerFactory was the software selected to model and analyze the electric system. This commercial software for power system analysis allows modeling electrical components of a power grid at all levels (generation, transmission, distribution, and load). It also provides several tools to study the integration of renewable resources at different points in the system. Both long-term (e.g., power flow) and short-term (e.g., short circuit, stability, and harmonics) studies can be performed.

This work presents the process to build a power system model not only considering technical data, but also social data, as well in order to create a more integrative planning perspective. This work is also applicable in locations where system data are not available, either because the utility does not cooperate with outside stakeholders, or because there are limited planning resources. For such instances, this paper presents a roadmap that can facilitate the planning work of diverse groups working towards an increased use of

renewable energy. Tropical and subtropical regions of the world will find this paper useful, since most likely those places have similar insolation levels as the case study presented. Literature on the integration of renewable energy to the grid is dominated by studies of regions within large, interconnected power systems. However, comprehensive work related to isolated/islanded and remote locations that have low-inertia power systems is very limited. Conditions are very different on low-inertia power systems, their limited capability to deal with the stability and control challenges of variable energy sources provide a challenging testing context for new ideas because problems would surface faster and are more critical than in large inertia systems. Thus, the novelty of this work is the focus on integrating social aspects to a comprehensive engineering modeling effort and the method presented in this section and applied on a case study. This will contribute to the electric energy transitions of locations having aggressive renewable energy goals (e.g., 100% renewable) as well as islanded and remote locations with low-inertia grids.

2.1. Modeling the Puerto Rico Generation Fleet

In Puerto Rico, the power system is dependent on imported fossil fuels to operate conventional generators on the island; the most common fuels used are No. 6 fuel oil, natural gas, coal, and diesel. Figure 3 shows the distribution of generating sources for the fiscal year (FY) 2014 [26]. This distribution was considered to keep correlation with the most current demand data publicly available from 2010 to 2014.
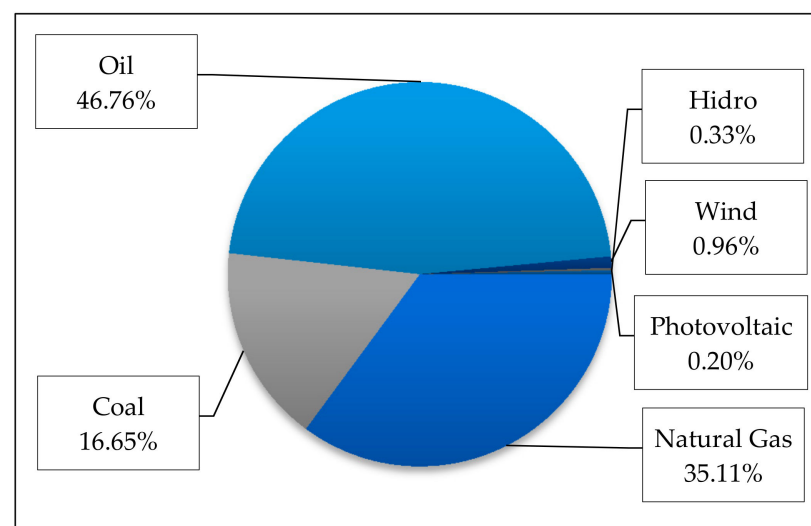

Figure 3. Distribution of generating sources for FY 2014.

Some of the generators' characteristics will be more critical than others depending on the type of study. For example, for dynamic analyses, the generator's ramp rates are considered in order to simulate the transition from one power output to another in a given period. In planning studies, the power plant heat rate, a measure of an energy plant's thermal efficiency in converting fuel to electricity, can be taken into account to evaluate future scenarios that optimize generators' dispatch.

PREPA's Integrated Resource Plan (IRP) from 2018 [27] was used as a data source on existing and currently available generators. Table 1 presents key data for the conventional generators used in the model and in simulations. The generators' maximum capacity, the voltage level at terminals, and connection buses were considered. These generators were simulated as synchronous machines connected to the grid.

Table 1. Existing conventional generators in Puerto Rico.

Name	Type of Fuel	Heat Rate at Max Capacity (BTU/kWh)	Up and Down Ramp Rate (MW/h)	Max Capacity (MW)
AES ST	Coal	9791	0	454
AGUIRRE 1 ST	No. 6 fuel oil	9600	300	450
AGUIRRE 2 ST	No. 6 fuel oil	9700	300	450
AGUIRRE GT21 & GT22	Diesel	14,400	120	42
AGUIRRECC 1 CT 1	Diesel	11,140	300	50
AGUIRRECC 1 CT 2	Diesel	11,140	300	50
AGUIRRECC 1 CT 3	Diesel	11,140	300	50
AGUIRRECC 1 CT 4	Diesel	11,140	300	50
AGUIRRECC 1 ST	Diesel	11,140	300	96
AGUIRRECC 2 CT 1	Diesel	11,140	300	50
AGUIRRECC 2 CT 2	Diesel	11,140	300	50
AGUIRRECC 2 CT 3	Diesel	11,140	300	50
AGUIRRECC 2 CT 4	Diesel	11,140	300	50
AGUIRRECC 2 ST	Diesel	11,140	300	96
CAMBALACHE 2 GT	Diesel	11,549	120	83
CAMBALACHE 3 GT	Diesel	11,549	120	83
COSTA SUR 5 ST	Natural gas	9747	300	410
COSTA SUR 6 ST	Natural gas	9747	300	410
COSTASUR GT11 & GT12	Diesel	14,400	120	42
DAGUAO GT11 & GT12	Diesel	14,400	120	42
ECOELECTRICACC CT 1	Natural gas	7497	600	157.5
ECOELECTRICACC CT 2	Natural gas	7497	600	157.5
ECOELECTRICACC ST	Natural gas	7497	600	192
JOBOS GT11 & GT12	Diesel	14,400	120	42
MAYAGÜEZ 1 GT	Diesel	9320	360	55
MAYAGÜEZ 2 GT	Diesel	9320	360	55
MAYAGÜEZ 3 GT	Diesel	9320	360	55
MAYAGÜEZ 4 GT	Diesel	9320	360	55
PALO SECO 3 ST	No. 6 fuel oil	9725	180	216
PALO SECO 4 ST	No. 6 fuel oil	9725	180	216
PALOSECO GT11 & GT12	Diesel	14,400	120	42
PALOSECO GT21 & GT22	Diesel	14,400	120	42

2.2. Modeling the Puerto Rico Power Network

The data needed to model the entire transmission and sub-transmission network was collected through meticulous research on the existing lines and transformers. On the one hand, the 230/115 kV transmission network was modeled using data from references [28,29]. On the other hand, the capacity and length of the 38 kV sub-transmission lines were obtained using georeferenced data from [30]. The main input parameters required by DIgSILENT PowerFactory and most of the power system analysis software to model transformers and lines are presented in Tables 2 and 3.

During the execution of balanced AC power flows, the automatic voltage tap changing of transformers was considered to maintain appropriate voltage levels (0.95 p.u. < v < 1.05 p.u.) at the buses. According to each transformer setting, the tap-winding was selected on the high voltage side or the low voltage side. The upper and lower voltage level adjustments were set to +/− 10% for all transformers, and the voltage control was carried out using 1.25% of additional voltage per tap.

For power line modeling, rated voltages and current capacities were required. Additionally, in DIgSILENT PowerFactory, typical line models can be created using resistances and reactances in ohm/km. With these values, the power system lines with the same configuration and size could be generated using a typical line model, adjusting the line's length in kilometers, the number of parallel lines, and a derating factor.

Table 2. Input parameters to model transformers.

Parameter	Units
Technology (Three Phase/Single Phase/Single Wire Earth Return)	NA
Rated Power	MVA
Nominal Frequency	Hz
Rated High Voltage	kV
Rated Low Voltage	kV
High-Voltage Side Vector Group (Y/YN/Z/ZN/D)	NA
Low-Voltage Side Vector Group (Y/YN/Z/ZN/D)	NA
Phase Shift	Degree
Positive and Negative Sequence Resistance	p.u.
Positive and Negative Sequence Reactance	p.u.
Zero Sequence Resistance	p.u.
Zero Sequence Reactance	p.u.
Automatic Tap Changing (Yes/No)	NA
Tap Position	NA
Additional Voltage per Tap	%
Voltage Setpoint	p.u.
Upper Voltage Bound	p.u.
Lower Voltage Bound	p.u.
Parallel Transformers	Unit
Rating Factor	%

Table 3. Input parameters to model lines.

Parameter	Units
Rated Voltage	kV
Rated Current	kA
Nominal Frequency	Hz
System Type (AC/DC)	NA
No. of Phases (1/2/3)	NA
No. of Neutral (0/1)	NA
Positive and Negative Resistance	Ohm/km
Positive and Negative Reactance	Ohm/km
Zero Sequence Resistance	Ohm/km
Zero Sequence Reactance	Ohm/km
Length of line	km
No. Parallel Lines	Units
Derating Factor	%

The distribution network model's development considered the 13.2 and 8.32 kV levels for this study. These voltage levels represent almost half of the circuit miles in the distribution system of Puerto Rico [25,31]. The remaining existing distribution feeders are mostly 4.16 kV, which are not optimal for high DERs penetration in Puerto Rico [32]. Higher voltages are needed to maximize local, renewable energy use, supporting the assumption made in this work of integrating PV at 13.2 and 8.32 kV. The 4.16 kV loads were modeled as aggregated loads connected to the corresponding transmission substations.

Although public information related to an existing distribution system might be minimal, representative feeder designs could be utilized as a general representation of the distribution system. For example, in this study, a typical feeder design used in a previous study was considered to model the distribution system [32]. The selected feeder represents about 35% of the distribution lines commonly found in Puerto Rico and could be operated at 13.2 or 8.32 kV [33]. The distribution line consisted of one main feeder with a total length of 10 km and three lateral branches connected at 2.5 km intervals along the main feeder with a total distance of 1.2 km each.

The main feeder has three different types of conductors. The first 3.25 km were modeled using a 556 ACSR conductor. A 266 ACSR conductor was used to represent the

second 3.25 km section. Finally, the rest of the mainline was modeled using 1/0 ACSR with a final 0.75 km segment of 4 CU HD. On the other hand, the three lateral branches have 1/0 ACSR for the first half and 4 CU HD for the rest. The distribution feeders were connected to the low-voltage side of 115/13.2 kV, 115/8.32 kV, 38/13.2 kV, and 38/8.32 kV substations.

Buses along feeders were located at the transition points between conductors (i.e., the end of one type of conductor and the beginning of a new one). Other buses correspond to customer connections to the distribution system. The electricity consumed by customers was represented as load, while the energy provided by PV systems was modeled as power sources. Initially, DERs can be set with the actual power output for the validation process and subsequently modified for research purposes. Figure 4 shows the simulated feeder with load connections (as arrows) and PV systems (as rectangles). Both loads and PV systems were evenly connected to the main feeder and the three lateral branches. Similarly, customers' electricity consumption and the energy production by PVs (if any) were also evenly distributed along the line.
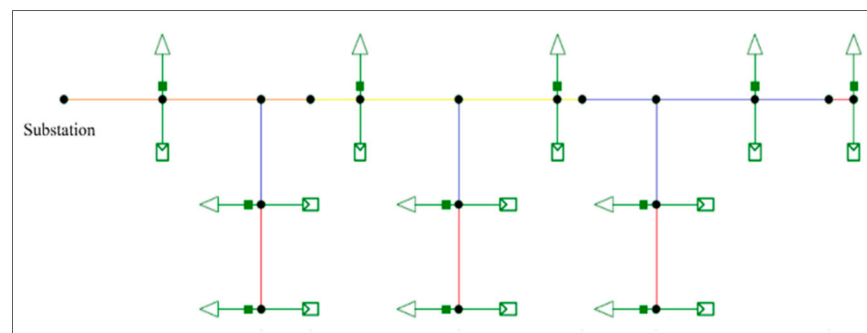

Figure 4. Distribution feeder considered for both 13.2 and 8.32 kV levels.

Using a 556 ACSR conductor (rating of 730 A) as the highest-rated conductor, the simulated feeder's calculated capacity was roughly 16 MVA for 13.2 kV connections and 11 MVA for 8.32 kV connections. The number of feeders connected to a substation depends on the transformer capacity. For security factors, one feeder was connected for every 10 MVA of transformer capacity. The above consideration was made for both the 13.2 and 8.32 kV levels. In this way, a total of 194 13.2 kV feeders and 52 8.32 kV feeders were simulated for the distribution system. A total of 246 distribution feeders, as shown in Figure 4, were created. The resulting model is accurate enough to study transmission-distribution interactions in the presence of DERs.

2.3. Modeling the Demand Profile

Power flow studies require not only to know electrical component capacities but also the electricity demand connected to each substation. Both tasks could be complex in isolated, low-inertia power systems with limited access to system data from utilities. However, for the demand profile in an island-type power system, the load consumption percentages for each of the buses in municipalities could be estimated from municipal, district, socio-economic, or community data. This section presents the result from a study completed on electricity use patterns in Puerto Rico to simulate the consumption of loads connected to every substation.

Electric utility customers are classified into residential, commercial, industrial, agriculture, public lighting, and other public authorities. Data related to customer class consumption are available, but the municipalities' demand breakdown is not readily available, thus the use per municipality had to be determined. The distribution of the total energy demand among the substations was made using the regional load estimates and considering historical consumption data (from 2010 to 2014), provided by PREPA (the

most recent electricity demand data reported by PREPA during the development of this study) [34]. Figure 5 shows the historical electricity consumption by class in Puerto Rico.
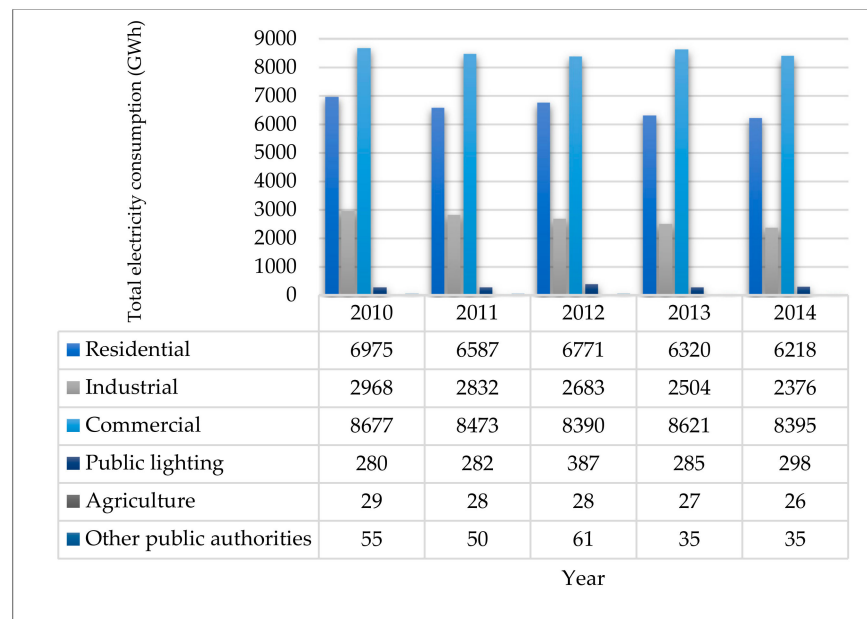

Total electricity consumption (GWh)	2010	2011	2012	2013	2014
■ Residential	6975	6587	6771	6320	6218
■ Industrial	2968	2832	2683	2504	2376
■ Commercial	8677	8473	8390	8621	8395
■ Public lighting	280	282	387	285	298
■ Agriculture	29	28	28	27	26
■ Other public authorities	55	50	61	35	35

Figure 5. Historical PREPA electricity consumption (from 2010 to 2014) by customer classes.

On average, the commercial sector has the highest consumption of electricity at almost 47%. The second and third positions are the residential class at 36% and the industrial class at 14.7%. Agriculture, public lighting, and other public authorities demand 2.1% of the total annual electricity. In addition to the above information, different municipal parameters were considered to calculate the electricity consumption by customer class within each municipality. Socio-economic and demographic variables like industrial activities, population, housing, and infrastructural projects are data of considerable significance that heavily influence the electricity consumption patterns of a power system [35]. Data from the census, local agencies and authorities, and government entities were used as influential factors for distributing the electricity consumption by classes (Figure 5) among the dispersed substations throughout the municipalities. For example, to estimate the distribution of 36% of the total electricity consumption by municipalities regarding the residential demand, it was assumed that the resident population in Puerto Rico's municipalities is directly proportional to the electricity demand. On the other hand, to distribute 47% of the total electricity consumption by municipalities regarding the commercial demand, it was assumed that the average employment in Puerto Rico's municipalities is also proportional to the electricity consumption. Table 4 shows the parameters previously mentioned for the allocation of demand by region.

Table 4. Parameters considered to the calculation of electricity consumption by municipalities.

Customer Class	Parameter
Residential	Annual estimates of the resident population: 2010 to 2014 [36].
Commercial	Trimestral average employment: 2010 to 2014 [37].
Industrial	Annual production workers: 2011 to 2015 [38].
Public lighting	Municipal public lighting per square mile: 2010 to 2014 [39].
Agriculture	Total cropland (cropland-harvested and cropland-pasture): 2012 [40].
Other public authorities	Total municipal facilities electricity consumption per square mile: 2010 to 2014 [41].

2.4. Distributed PV Integration Modeling

To evaluate the impacts of high renewable penetrations in an existing power system, it is crucial to identify the available renewable sources in each region and whether there are favorable conditions to take advantage of those resources. In Puerto Rico, there are many ways to generate electricity through renewable energy resources. Biomass, micro-hydro, ocean, solar radiation, solar thermal, and wind are viable means of producing renewable energy on the island, demonstrated by research estimates [5]. The solar resource was identified as economically feasible, thus this work assumed PV systems as the optimal way to support the electricity supply in regular operation and after catastrophic events when the power system could be divided into mini regions. Puerto Rico receives a high insolation level, more than 20 MJ/m^2 (average daily global insolation per year) in some areas, which means that the island has an excellent solar resource that can be exploited. Besides, PV systems do not produce noise (compared with wind generators) and are the least environmentally intrusive technology. Finally, although the required surface area to install PV systems could be a concern because of Puerto Rico's size, the PV installation on rooftops is a practical way to address this concern [5].

Actual irradiance and temperature data collected from diverse Puerto Rico areas were used to estimate the PV output under different scenarios and irradiance conditions. The potential PV production was used to assign the installed capacity of PV systems around the main island. Each PV system's installed capacity varied according to the evaluated scenario (PV penetration levels). Meanwhile, an irradiance study was developed to identify a typical PV system output during a sunny day and a cloudy day. Irradiance data was used to determine the PV output in each of the scenarios.

2.5. Potential PV Production Using the Electric Power System Model

Two factors are significant to determine the potential electricity production by PV systems in a given area. On the one hand, the average irradiance per year or insolation estimated on municipalities indicates how much electricity can be produced by PV systems. On the other hand, the available surface area represents another significant parameter to calculate the potential electricity production by PVs. The insolation in each municipality was obtained using the System Advisory Model (SAM) software of the National Renewable Energy Laboratory (NREL). For the available residential rooftop area, 2017 census data estimates were used, considering single unit-detached and single unit-attached housings [42]. According to SAM, the top 10 list of the municipalities with the highest average daily global insolation per year is shown in Table 5. Santa Isabel is the municipality with the highest average insolation in Puerto Rico.

Table 5. Top 10 list of the municipalities with the highest average daily global insolation per year (Data from [43]).

Municipality	Area	Latitude (DD)	Longitude (DD)	Global Horizontal Insolation (W/m^2)
Santa Isabel	A5	17.97	−66.42	241.58
Loiza	A3	18.41	−65.86	241.17
Guánica	A6	17.97	−66.90	239.92
Fajardo	A3	18.33	−65.65	239.50
San Juan	A1	18.45	−66.06	239.50
Hatillo	A7	18.49	−66.82	238.67
Guayama	A5	17.97	−66.10	238.25
Luquillo	A3	18.37	−65.70	238.25
Cataño	A2	18.45	−66.10	237.83
Arecibo	A7	18.49	−66.70	237.42

Residential rooftop areas were selected as a feasible surface to install PV modules without occupying limited land resources, a strategy previously proposed and currently

pursued by industrial, commercial and residential clients [5]. The percentage of occupied housing units and an uncertainty factor of 50% (non-available areas due to weak roof infrastructures or equipment that prevent the PV installation or cause shadows) were applied to the total of household units. Furthermore, a typical residential housing unit area of 152 m^2 was used for calculations. Figure 6 shows the distribution of the available residential rooftop area by region. Figure 7 presents a histogram of the average daily global irradiance per year received by the available residential rooftop area in Puerto Rico.
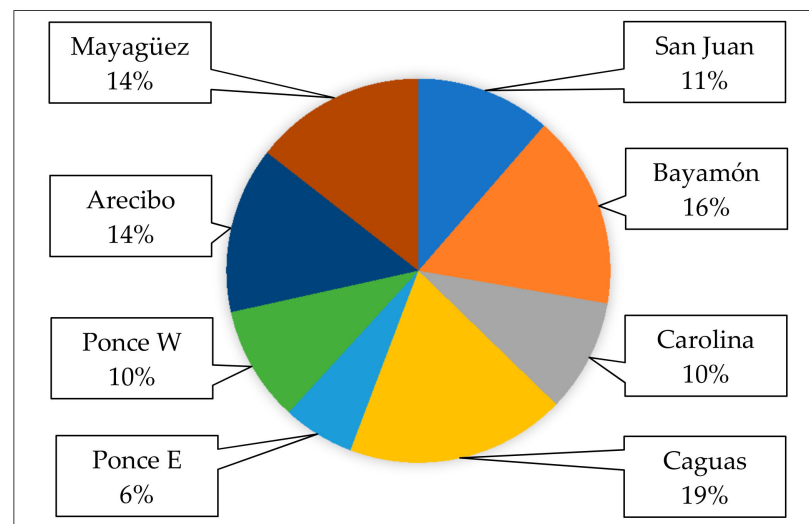

Figure 6. Available residential rooftop area by region in Puerto Rico in 2017.
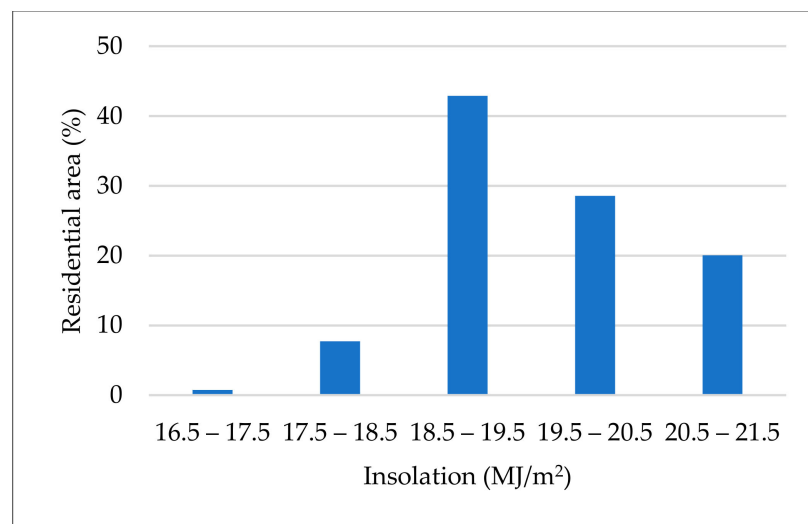

Figure 7. Histogram of the average daily global irradiance per year received by the available residential rooftop area in Puerto Rico in 2017.

The potential energy obtained from the insolation in each one of the municipalities was calculated using Equation (1) [5,44]. Likewise, Equation (2) was used to calculate the potential electricity production by PV systems [5,45]. Additionally, typical characteristics for PV systems and additional equipment parameters considered for calculations are shown in Table 6.

$$\text{DPEI} = \text{DAI} * \text{ARRA} \qquad (1)$$

where,

DPEI is Daily Potential Energy obtained by Insolation on the terrestrial surface (kWh/day),

DAI is Daily Average Irradiance per year (kWh/m^2/day),
ARRA is Available Residential Rooftop Area (m^2).

$$DPEP = DPEI * \eta_{rated} * [1 - TC\eta(T_C - T_N)] * \eta_{inv} * \eta_{loss} \tag{2}$$

where,

DPEP is Daily Potential Electricity Production by PV systems (kWh/day),
DPEI is Daily Potential Energy obtained by Insolation on terrestrial surface (kWh/day),
η_{rated} is PV module efficiency,
$TC\eta$ is Temperature coefficient (%/°C),
T_C is Operating PV module temperature (°C),
T_N is Operating PV module at Standard Test Conditions (25 °C),
η_{inv} is Inverter efficiency,
η_{loss} is Efficiency for losses.

Table 6. Typical PV and equipment parameters.

Parameter	Value
η_{rated}	0.14
$TC\eta$ (%/°C)	0.40
TC (°C)	25
η_{inv}	0.95
η_{loss}	0.95

2.6. PV Production Conditions for Different Times

As the insolation is not constant during the day, identifying cloudy and sunny days is required to evaluate each possible situation. Additionally, spatial variability of solar energy needs to be also considered because of the changing and inconsistent irradiance over the territory at the same time.

In this study, the National Solar Radiation Database, created by NREL, was the primary data source to gather annual irradiance information for five geographically dispersed locations in Puerto Rico: San Juan, Ceiba, Ponce, Aguadilla, and Mayagüez [46]. Since there is no irradiance data for each municipality, the assumption that a group of municipalities (areas) could have the same average irradiance at specific times was made as an acceptable initial approach to consider the spatial variability of solar radiation. This assumption is supported by a 2009 study on the potential of renewable energy in Puerto Rico [5]. The datasets used to model the irradiance in each area are shown in Table 7.

Table 7. Datasets from NREL used for each area.

Area	Used Dataset
San Juan	San Juan
Bayamón	San Juan
Carolina	San Juan
Caguas	Ceiba
Ponce E.	Ponce
Ponce W.	Ponce
Arecibo	Aguadilla
Mayagüez	Mayagüez

One-hour irradiance data was processed to identify sunny and cloudy days and to simulate different irradiance conditions for the same evaluated case. The sky clearness index k was used for the irradiance characterization. This index is defined as the ratio of instant global horizontal irradiance (I_{GHI}) to the maximum theoretically possible extrater-

restrial irradiance (I_{ETI}). Thus, the sky clearness index can be calculated through Equation (3), and the daily sky clearness index k_D could be calculated using Equation (4) [47].

$$k_D = \frac{I_{GHI}}{I_{ETI}} \tag{3}$$

$$k_D = \frac{\int_{t_{rise}}^{t_{set}} (I_{GHI}) dt}{\int_{t_{rise}}^{t_{set}} (I_{ETI}) dt} \tag{4}$$

The daily sky clearness index was jointly used with the daily probability of persistence (POP_D), proposed by [48], which indicates the stability level of a daily irradiance dataset for a fixed time interval. The higher the value of POP_D, the smaller the irradiance variability. An algorithm was developed to process annual irradiance data and to facilitate the characterization of all days. The process to calculate the POP_D with one-hour irradiance data are the following:

1. Calculate the instantaneous clearness index k for each hour, as described in Equation (3), and round off at the first decimal place.
2. Count the times of identical adjacent clearness index k.
3. Divide the result obtained in step 2 by the number of hours from sunrise to sunset.

There are many ways to categorize daily weather using k_D and POP_D indexes [48,49]. However, Table 8 shows the two minimal categories that could be considered to classify daily irradiance conditions and applied for similar studies with available irradiance data.

Table 8. Classification parameters of daily irradiance using k_D and POP_D indexes.

k_D	POP_D	Description	Type of Day
≥0.5	≥0.5	Sunny with steady sky conditions for almost the entire day.	Sunny
<0.5	<0.5	Cloudy with high levels of fluctuation for the entire day.	Cloudy

3. Results

Following the methods described on Section 2 resulted in an electric power system model with a total of 4535 buses used to simulate the Puerto Rico power system. A summary of all the simulated power lines and transformer substations is presented in Tables 9 and 10. Figure 8 shows the final version of the one-line diagram of the Puerto Rico power system. In this figure, voltage levels are identified by colors.
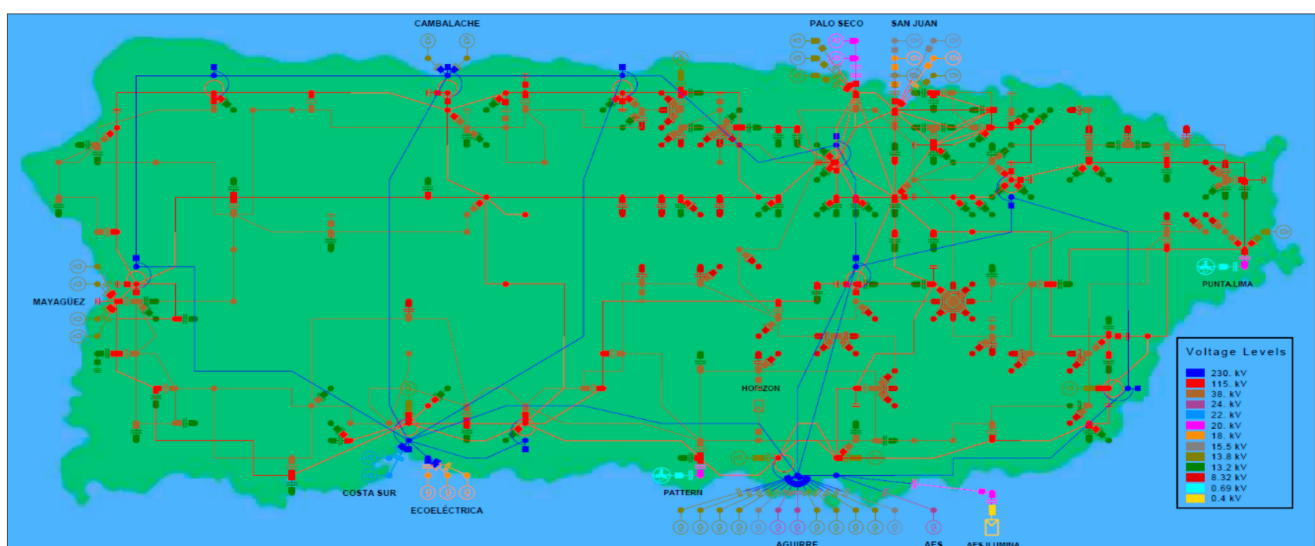

Figure 8. One-line diagram of the Puerto Rico electric power system (230 kV—blue; 115 kV—red; 38 kV—brown; 13.2 kV—green; 8.32 kV—burgundy).

Table 9. Summary of the simulated electrical lines.

Process	Voltage Level (kV)	Number of Lines
Transmission	230	17
	115	102
Sub-transmission	38	100
Distribution	13.2	3298
	8.32	884
Total	NA	4401

Table 10. Summary of the simulated transformer substations.

Type of Transformer Substation (kV/kV)	Number of Substations
230/115	11
230/24	3
230/22	2
230/20	1
230/18	3
230/15.5	2
230/13.8	10
115/38	44
115/20	4
115/18	2
115/15.5	2
115/13.8	15
115/13.2	56
115/8.32	4
38/13.2	27
38/8.32	48
Total	234

Additionally, the power system was divided into eight areas or regions, representing the actual operational divisions of PREPA. These regional divisions facilitate the analysis and presentation of overall results in this paper. The simulated power system divided by areas is shown in Figure 9. The smaller islands of Vieques and Culebra are energized through an submarine 38-kV line from Naguabo. Due to their low electricity consumption, they were not considered to simplify the simulations; however, this does not considerably affect the results.
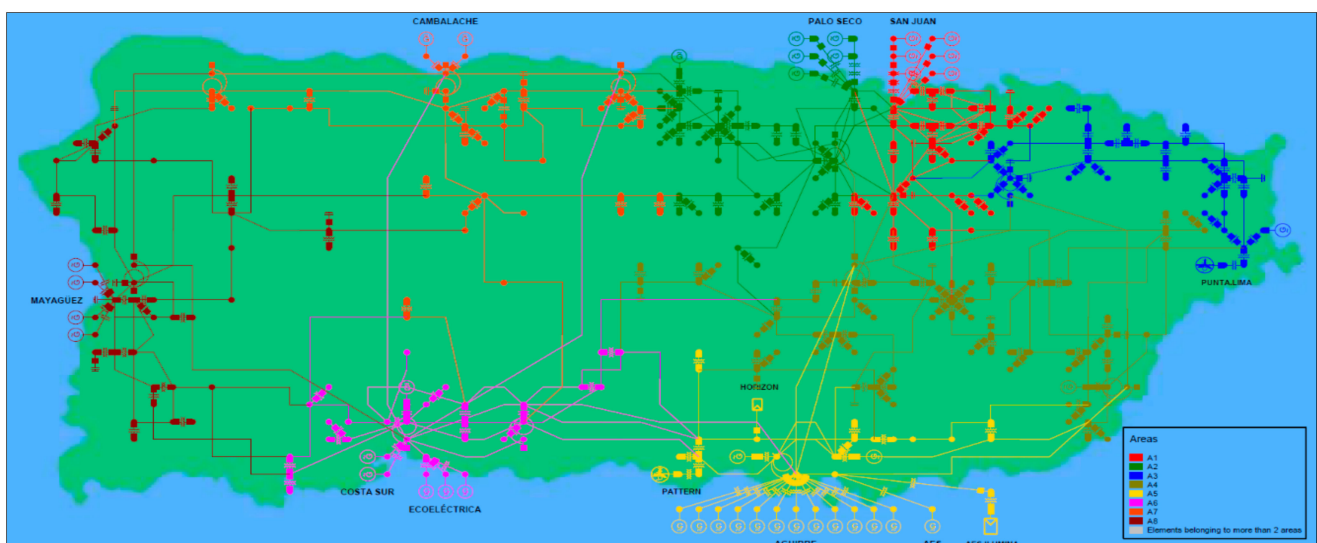

Figure 9. One-line diagram of the Puerto Rico electric power system divided by regions.

The resultant demand distribution of electricity consumption by regions is summarized in Figure 10. This graphic shows that just the San Juan region consumes almost a quarter of the total electricity demand of Puerto Rico. These percentages were used to assign the load (MW) connected to each substation, multiplying the peak load (depending on the evaluated case) times the factor calculated for each municipality. Compared to the most recent region's demand distribution presented in [27], the distribution estimated through this work differs by 1.5% on average regarding all areas.
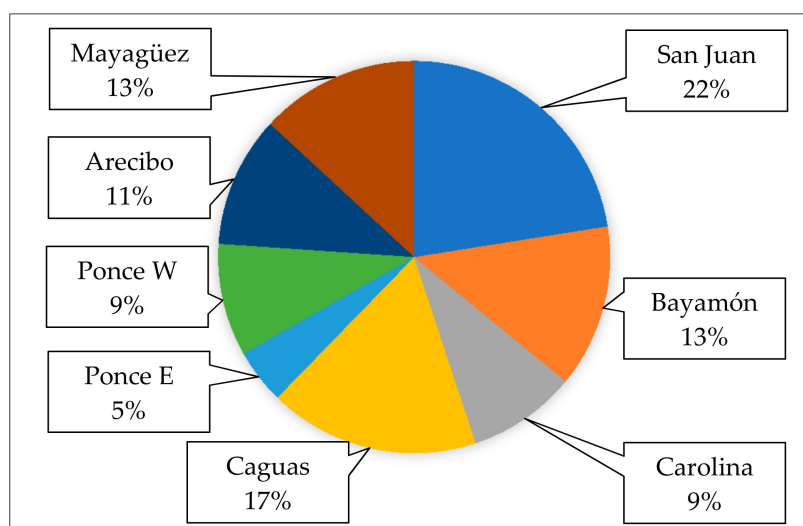

Figure 10. Resultant distribution of electricity consumption in Puerto Rico by region (based on available data from 2010 to 2014).

3.1. Validation of the Power System Model

Public data were used to simulate a typical system operation at 9 a.m., 12 p.m., and 3 p.m. to validate a base scenario of the simulated power system [27,34,50]. In order to calibrate the base scenario, the system loads and generation dispatch were adjusted to simulate usual conditions of the system. The daily peak load was calculated based on the average load factors reported by PREPA from 2010 to 2014 [34]. Then, this load factor was extrapolated, using the demand forecast of the PREPA's 2019 IRP to obtain the 2019 peak load [27].

The demand forecast, used in the PREPA's 2019 IRP, includes technical losses. In contrast, the work described in this paper did not consider technical losses in the calculated peak load because they are simulated for each electrical component. The estimated 2019 peak load was 2470.7 MW. Finally, the typical daily load profile of Puerto Rico, presented in Figure 11, was used to get the load level at 9 a.m. (2100 MW), 12 p.m. (2322 MW), and 3 p.m. (2310 MW).

For the base scenario's validation, typical generation dispatches were used to carry out a power flow analysis and check if all electrical measurements (e.g., buses voltage, lines loading, and generating plants loading) were between acceptable security limits as occurs in regular operation [50]. The selected generation dispatches, which maintain the generation-demand balance, are shown in Table 11. In the simulation, Aguirre 1 ST generator was assigned as the slack generator that supplies as much real power and reactive power as required to maintain the generation-demand balance while keeping the voltage constant at its bus.
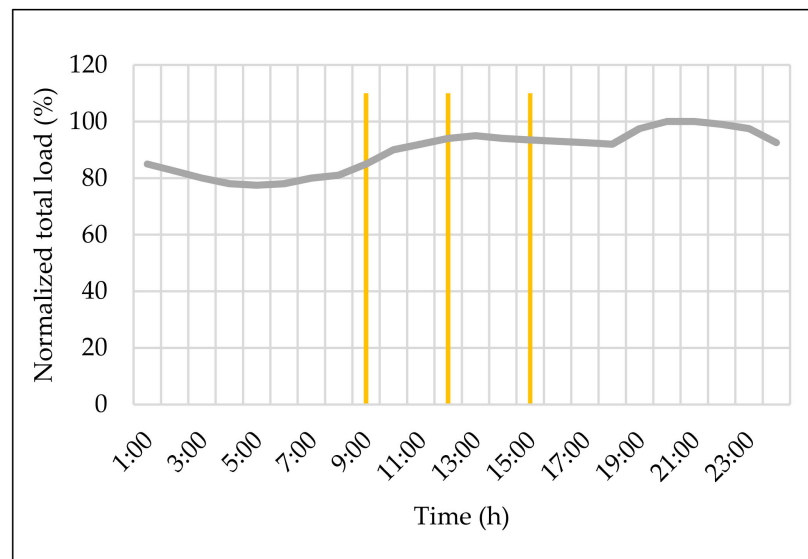
Figure 11. Typical weekday normalized load shape in Puerto Rico (Data from [27]).

Table 11. Typical generation dispatches used for the validation process.

Name	Generation at 9:00 A.M. (MW)	Generation at 12:00 P.M. (MW)	Generation at 3:00 P.M. (MW)
AES ST	454	454	454
AGUIRRE 1 ST	290	360	360
COSTA SUR 5 ST	270	330	330
COSTA SUR 6 ST	270	330	330
ECOELECTRICACC CT 1	154.6	144	144
ECOELECTRICACC CT 2	154.6	144	144
ECOELECTRICACC ST	154.6	144	144
PALO SECO 3 ST	40	75.5	75.5
PALO SECO 4 ST	40	75.5	75.5
SAN JUAN 7 ST	71	86.5	86.5
SAN JUAN 8 ST	71	86.5	86.5
SAN JUANCC 6 CT	130	150	150
SAN JUANCC 6 ST	43	49	49
Total (MW)	242.8	2429	2429

PV systems were set as zero power output for the validation process, representing the minimal energy currently supplied by PV-based DERs in Puerto Rico. In order to verify the model, we needed to develop a base scenario to be compared with previously validated models. This base scenario was simulated to mimic the conditions of the system more than ten years ago (when the renewable-based electricity production on the island was almost zero). In fact, the PV-based production has not greatly increased since then; it currently represents just under 5% of the total installed capacity of generation on the island. This emphasizes the need to prove the feasibility of integrating more renewable energy into the grid, especially since now there is a 100% renewable energy goal for 2050 [51].

Balanced AC power flows were executed considering automatic tap adjustment of transformers, automatic shunt adjustment, and reactive power limits. After running the power flows, results showed acceptable measurements in lines, transformers, generators, and most buses. Nevertheless, it was necessary to connect additional capacitor banks at some critical buses to obtain appropriate voltage values (0.95 p.u. < v < 1.05 p.u.). Capacitor banks were set to adjust their reactive production to support voltage regulation automatically. Table 12 shows the list of existing and added capacitor banks for base cases. These capacitor banks were considered in each one of the cases simulated through this

research and represent the aggregate, estimated effect of regulating equipment already installed in Puerto Rico's power system.

Table 12. List of existing and added capacitor banks in the simulated power system.

Terminal	Status	Municipality	Nom. Volt. (kV)	Qmax (MVAR)
MONACILLOS.115	Added	San Juan	115	50
BERWIND.38	Existing	San Juan	38	43
H.REY.115	Existing	San Juan	115	43
TOA.BAJA.38	Added	Toa Baja	38	20
S.LLANA.115	Existing	Carolina	115	38
S.LLANA.115	Added	Carolina	115	38
FAJARDO.115	Existing	Fajardo	115	29
A.BUENAS.115	Added	Aguas Buenas	115	50
AIBONITO.38	Added	Aibonito	38	30
CAGUAS.115	Existing	Caguas	115	43
CAYEY.115	Existing	Cayey	115	32
HUMACAO.115	Added	Humacao	115	50
OROCOVIS.38	Added	Orocovis	38	20
S.LORENZO.38	Added	San Lorenzo	38	30
YABUCOA.115	Existing	Yabucoa	115	38
CAMBALACHE.PLT.115	Added	Arecibo	115	50
CAMBALACHE.38	Existing	Arecibo	38	9
BARCELONETA.115	Existing	Barceloneta	115	36
MANATI.115	Existing	Manatí	115	43
VICTORIA.115	Existing	Aguadilla	115	36
ACACIAS.13.2—S1—30 MVA	Existing	Hormigueros	13.2	9
LARES.38	Added	Lares	38	30
MAYAGÜEZ.115	Added	Mayagüez	115	30
MAYAGÜEZ.PLT.115	Existing	Mayagüez	115	53

Results for the 230-kV level at noon are presented in Table 13. Similar results were observed in the other cases studied at 9 a.m. and 3 p.m. The lines AES.230—YABUCOA.230, AGUIRRE.230—A.BUENAS.230 (1 & 2), COSTA.SUR.230—CAMBALACHE.230, COSTA.SUR.230—MANATI.TC.230, and MAYAGÜEZ.230—COSTA.SUR.230 were the lines transmitting more electricity. The above represents a typical scenario because these lines are the north–south transmission lines that carry power from the major production facilities located on the south coast to the load centers in the north [25]. Furthermore, the base model developed in DIgSILENT for the transmission system was calibrated using a balanced model previously developed and validated in PowerWorld [28]. Thus, the base-case model yielded results close to actual data, and it is an appropriate representation to study the effects of high DER penetration in the combined transmission-distribution system of Puerto Rico.

Table 13. Power flow in 230-kV lines at 12 p.m. for the base scenario.

Line Name (From Terminal i to Terminal j)	Volt. Mag.—i (p.u.)	Volt. Mag.—j (p.u.)	Loading (%)	Current Mag. (kA)
A.BUENAS.230—BAYAMON.TC.230	0.98	0.98	10.92	0.25
AES.230—YABUCOA.230	1.01	0.98	28.59	0.66
AGUIRRE.230—A.BUENAS.230 (1)	1.00	0.98	23.16	0.54
AGUIRRE.230—A.BUENAS.230 (2)	1.00	0.98	23.20	0.54
AGUIRRE.230—AES.230	1.00	1.01	21.42	0.50
BAYAMON.230—MANATI.230	0.98	0.98	15.97	0.18
COSTA.SUR.230—AGUIRRE.230	1.01	1.00	14.87	0.18
COSTA.SUR.230—CAMBALACHE.230	1.01	0.97	44.62	0.52
COSTA.SUR.230—ECOELECTRIC.230	1.01	1.02	66.07	1.19
COSTA.SUR.230—MANATI.TC.230	1.01	0.98	40.27	0.47
COSTA.SUR.230—PONCE.230	1.01	1.01	57.75	0.33
MANATI.230—CAMBALACHE.230	0.98	0.97	10.27	0.12
MAYAGÜEZ.230—COSTA.SUR.230	0.96	1.01	51.55	0.60
MAYAGÜEZ.230—MORA.230	0.96	0.96	8.90	0.10
MORA.230—CAMBALACHE.230	0.96	0.97	14.31	0.17
S.LLANA.230—A.BUENAS.230	0.97	0.98	19.12	0.44
YABUCOA.230—S.LLANA.230	0.98	0.97	19.05	0.22
TOTAL	NA	NA	NA	7.00

3.2. Results of Potential PV Production Using the Electric Power System Model

Figure 12 shows the amount of annual electricity that could be produced by PV systems installed on residential rooftop surfaces (based on the Puerto Rico annual net electric energy production in 2014 [34]). These results showed that Puerto Rico's high insolation level is capable of displacing a large amount of conventional generation. This study, as well as another study by one of the authors completed in 2009, confirmed the availability and potential of residential rooftops to host large quantities of PV capacity and thus make a significant aggregate contribution to the archipelago's energy mix. Finally, the potential contribution to the daily electricity generation based on PV systems installed on residential rooftops by region was calculated and is summarized in Figure 13.
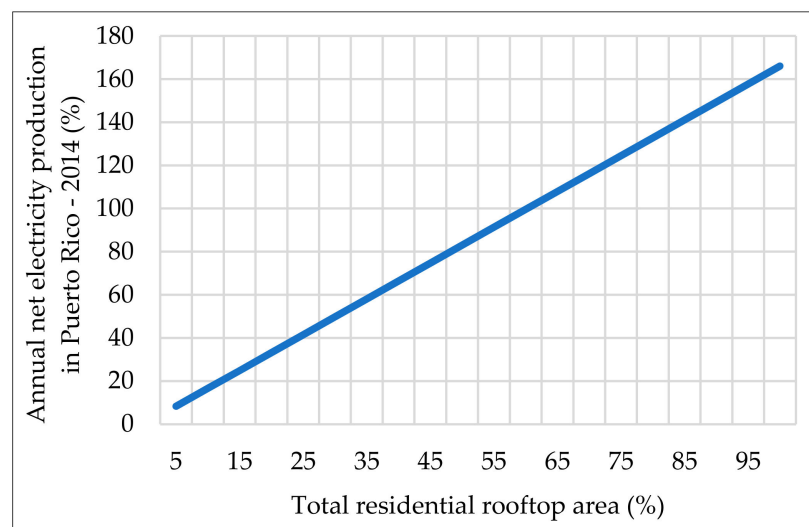

Figure 12. Annual electricity production by PV systems installed on residential rooftop surface (based on the Puerto Rico annual net electric energy production in 2014).
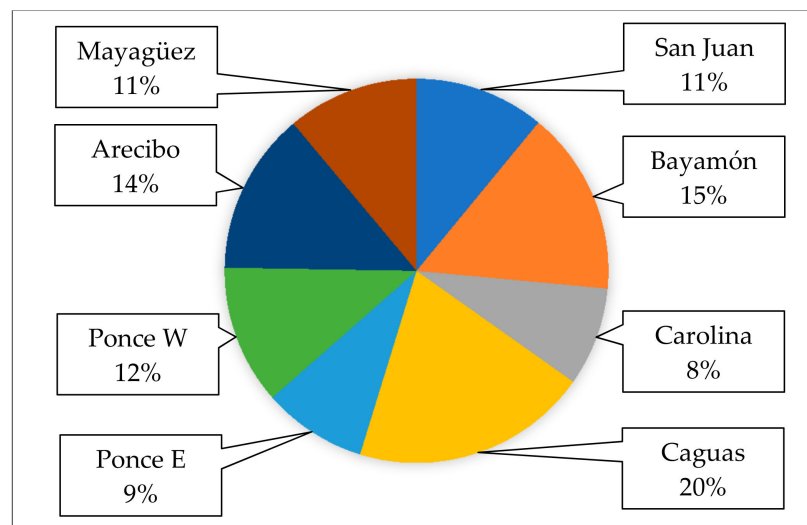
Figure 13. Resultant distribution of the potential electricity production by PV systems installed on residential rooftop surface by region in Puerto Rico in 2017.

The allocation of distributed PV (DPV) systems is of particular interest in planning and operation studies. The relation between electricity consumption (as shown in Figure 10) and the potential PV production by areas (as presented in Figure 13) is shown in Figure 14. According to this graph, areas with higher energy use have a higher potential for PV generation. However, although the San Juan area consumes the highest percentage of electricity, the limited available residential-rooftop area (11% of the total available area, according to Figure 6) restricts further PV generation.
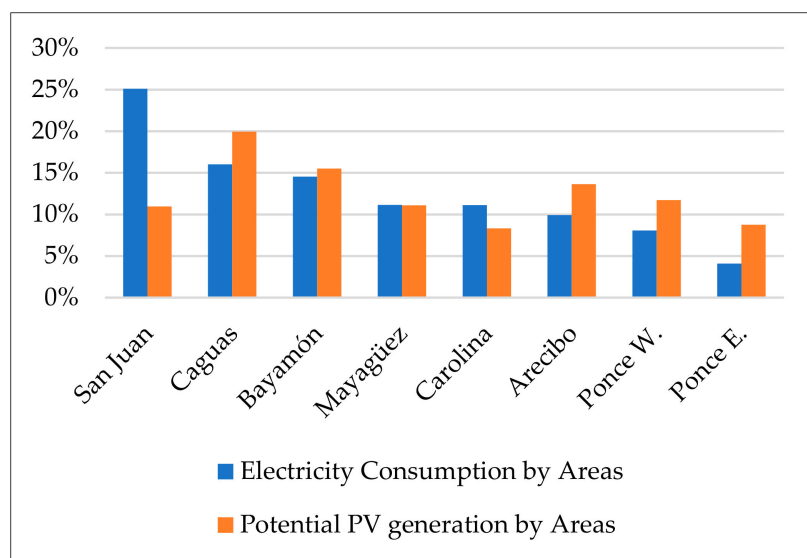

Figure 14. Relation between electricity consumption (based on available data from 2010 to 2014) and potential PV production by areas in Puerto Rico in 2017.

The resultant distribution of the potential PV production by municipalities in percentages obtained from this exercise was used to assign the potential installed capacity of PV projects dispersed around the island, multiplying the total PV production (depending on the level of PV penetration to be evaluated) times the factor calculated for each one of the municipalities. Then, the installed capacity calculated for each municipality was distributed among the distribution buses located in the corresponding area.

According to PREPA's 2019 IRP, the total demand forecast in 2019 (without technical losses) is 16,162 GWh [10]. Using this value, different annual PV penetration levels and the total PV installed capacity for each case can be calculated. The evaluation of distinct renewable integration scenarios to the grid can support the ordered transition and adaptation of centralized, fossil-based existing grids towards a new electric grid that maximizes renewable and local energy use. For example, a summary of three possible cases to be studied in Puerto Rico is presented in Table 14. The total PV installed capacity was calculated considering five peak sun hours per day. This represents a capacity factor of 20%, which is a common practice for PV designers and contractors in Puerto Rico, as well planners. Even the utility, which has never been particularly supportive of renewables, accepted a 20% capacity factor for distributed PV systems in a study commissioned to Siemens on demand side resources [27].

Table 14. Scenarios of PV penetration evaluated for all studies.

Scenario	Annual PV Penetration (%)	Annual PV Penetration (MWh)	Total PV Installed Capacity (MW)	Area Needed (m^2)
1	20	3,232,400	1771	19,274,780
2	30	4,848,600	2657	28,912,171
3	40	6,464,800	3542	38,549,561

3.3. Results of Potential PV Production for Different Times

A PV module's nominal capacity is defined as the maximum power output under the following conditions: instant in-plane irradiance received of 1000 W/m^2 and module temperature of 25 °C (these are the Standard Test Conditions, STC). A PV module's maximum power output could be obtained from the I-V curves at the STC temperature and varying irradiance levels. These curves show that the relation between the maximum power output and irradiance is approximately linear. Therefore, the power production of PV systems could be assumed directly proportional to irradiance [52].

To calculate the PV production at a specific time, the total PV installed capacity in municipalities, calculated and described in Section 3.2, was multiplied by the irradiance factor depending on the case (irradiance that were determined through the process described in Section 2.6). For example, PV systems located in the San Juan area could represent 11% of the total PV installed capacity in Puerto Rico (Figure 13). In sunny conditions at 9 a.m., San Juan area could receive 525 Wh/m^2 of irradiance; this means that PV systems could inject 52.5% of their installed capacity (considering STC conditions). Then, PV systems installed in the San Juan area, considering 20% of PV penetration (1771 MW of the total installed capacity in Puerto Rico and about 194 MW of total installed capacity in San Juan), would generate about 102 MW in sunny conditions at 9 a.m. when it receives 525 Wh/m^2.

Results of the exercise above is presented in Table 15, which contains the PV generation for other times and areas regarding a 20% PV penetration scenario. PV production in Puerto Rico's areas calculated for 30 and 40% scenarios at different times are shown in Tables 16 and 17. These results could be used to study diverse PV distributions in each area and to analyze their impacts on the regular operation of the Puerto Rico power system. PV allocation is a critical factor in determining the corrective actions required for the existing infrastructure to reduce operational risks. In the same way, various system operation strategies, that support a well-organized transition to a more fossil-independent system, could be initially implemented, encouraging the DER integration, while the existing infrastructure transformation is planned and conducted.

Table 15. Potential PV production by area (20% of PV penetration).

| Area | Active Power (MW) | | | | | |
| | Sunny Days | | | Cloudy Days | | |
	9 A.M.	12 P.M.	3 P.M.	9 A.M.	12 P.M.	3 P.M.
San Juan	102	182	157	52	82	41
Bayamón	132	266	213	38	69	130
Carolina	70	132	118	14	75	22
Caguas	152	289	251	37	77	184
Ponce E.	71	153	132	31	76	41
Ponce W.	99	207	168	22	82	98
Arecibo	121	223	185	24	130	46
Mayagüez	60	152	115	38	101	38
Total	806	1605	1341	256	693	599

Table 16. Potential PV production by area (30% of PV penetration).

| Area | Active Power (MW) | | | | | |
| | Sunny Days | | | Cloudy Days | | |
	9 A.M.	12 P.M.	3 P.M.	9 A.M.	12 P.M.	3 P.M.
San Juan	153	273	236	78	123	61
Bayamón	198	399	320	57	103	195
Carolina	105	198	177	21	113	33
Caguas	227	434	377	56	116	276
Ponce E.	106	229	199	47	115	61
Ponce W.	148	311	253	33	123	147
Arecibo	182	335	278	36	196	69
Mayagüez	90	227	173	56	152	57
Total	1209	2407	2011	384	1040	899

Table 17. Potential PV production by area (40% of PV penetration).

| Area | Active Power (MW) | | | | | |
| | Sunny Days | | | Cloudy Days | | |
	9 A.M.	12 P.M.	3 P.M.	9 A.M.	12 P.M.	3 P.M.
San Juan	204	364	315	104	163	81
Bayamón	264	532	427	76	137	260
Carolina	140	264	235	27	151	43
Caguas	303	579	503	75	155	368
Ponce E.	142	306	265	63	153	82
Ponce W.	197	414	337	44	164	197
Arecibo	242	446	370	47	261	92
Mayagüez	120	303	231	75	202	76
Total	1612	3210	2682	512	1386	1198

4. Discussion

The process to build a comprehensive power system model not only considering technical data, but also social data was presented. The main objective is to attain a more integrative planning perspective for electric energy transitions. This work is applicable in locations where system data are not available, either because the utility does not cooperate with outside stakeholders, or because there are limited planning resources. For such instances, this paper presents a roadmap that can facilitate the planning work of diverse groups working towards an increased use of renewable energy.

As a case study that used the proposed integrative perspective, the generation, transmission, and distribution systems of Puerto Rico were modeled, yielding a powerful tool for evaluating DER effects on the regular operation of the electrical grid. It was necessary

to do an exhaustive search about existing and available conventional generators, existing transmission lines, distribution lines, and transformers to model the whole system. A typical distribution feeder design, at either 13.2 or 8.32 kV, representing almost half of the circuit miles operating at the distribution system, was used to consider the interplay between the transmission and the distribution systems. This assumption was made considering that previous studies have identified voltages over 4.16 kV as most suitable for PV integration in Puerto Rico. Thus, the distribution part of a model to study the impacts of DERs on the bulk system operation should be mainly based on those feeders most likely to host large quantities of distributed PV. In total, 234 transformer substations and 4401 lines were modeled, simulating the power system as realistically as possible.

Undoubtedly, the lack of public information was the main challenge for the study of the entire system, primarily to represent the demand connected to each substation. Historical consumption data reported by the power system operator, municipal information, census data, socio-economic indicators, and planning information from the state government were considered to calculate an approximate distribution of the total energy demand among the substations. Additionally, the validation process was carried out through a power flow analysis using typical generation dispatches, the average daily energy demand at three different times, and the load distribution. Balanced AC power flows were executed to check if all electrical parameters (e.g., bus voltage, lines loading, and generating plants loading) were between acceptable security limits. In the same way, the model yielded results close to data corroborated in a previous (simpler) study, confirming the model's validity because of the approximation of the power flow's results with the actual system operation.

This work proved that Puerto Rico's high insolation level could displace a large amount of conventional generation. Results showed that the annual net electricity generation in Puerto Rico could be produced by 60% of PV systems installed on residential rooftop surfaces (based on the Puerto Rico annual net electric energy production in 2014 [34]). There are other technical and social considerations needed to be addressed to fulfill that 60%; however, estimates show the potential of rooftop PV and serve as motivation to continue working towards an increased use of distributed PV. Furthermore, the contribution to the daily electricity generation based on PV systems installed on residential rooftops by region was calculated and presented in this work. The east-central area is the region that can generate the highest amount of electricity. However, all municipalities on the island can likewise participate in the transition of the existing fossil-dependent generation to a more diverse fuel portfolio, including renewable energy resources distributed close to demand centers.

Results of the potential PV production by areas at different times, based on irradiance information, daily weather data, and the available residential rooftop area, were presented in this work. This information shows that considering a 30% PV penetration scenario at noon on a sunny day, the electricity production by PV systems can reach almost the 2019 estimated daily peak (2470.7 MW). Even though this scenario can represent a challenge due to the existing low-inertia power plants in Puerto Rico, the design and application of strategies to take advantage of the significant amount of PV production during the day could support the grid's transition. For example, the installation of storage and demand response programs could efficiently address the PV curtailment resulting from the existing system's constraints. Additionally, these results could be used to study the optimal allocation of PV systems in each area and to evaluate their effects on the regular operation of the Puerto Rico power system. For instance, preliminary results of an ongoing study indicate that fewer alterations of the steady-state magnitudes occur with more distributed PV systems connected to a higher voltage level. Finally, by connecting the rooftop PV systems at 13.2 or 8.32 kV, the model will not have most of the technical difficulties previously identified for 4.16 kV feeders in Puerto Rico (such as problems with voltage regulators).

The novelty of this work is the focus on integrating social aspects to a comprehensive engineering modeling effort and the method itself applied on a case study. Electric power systems can produce both social justices and injustices, depending on a diversity of social and technology factors. Thus, a transition to a renewable-based power must be supported by appropriate physical and social infrastructures [23]. To achieve that, a balanced analysis of advantages and disadvantages must be completed. Some of the key issues that must be discussed: length and phases of the transition toward renewables; options of energy resources and technologies; positive/negative impacts; potential strategies and actions; funding sources; among others [23]. The comprehensive power system model presented in the paper, which was created using socio-economic data, would be a critical tool in the analysis and discussion among energy stakeholders with diverse backgrounds. Furthermore, low-inertia systems such as those in islanded or remote locations have an even more critical need to determine and analyze the social and technical consequences of integrating more renewable energy into their conventional grids. The reason being the high electricity costs usually found on those locations, and the need to move to cheaper and more resilient options. The process and integrative perspective used in this work could be adapted to those remote contexts, using as a guide the case study presented.

The method's applicability goes beyond the specific case study of Puerto Rico. This work broadens the typical power system modeling to include planning and social considerations. The method used in this paper allows for interdisciplinary teams to work in the development of a model as part of broader design goals for a renewable-dominant energy system. For example, the identification of data sets is a critical interdisciplinary task since the socio-economic factors guide the power system modeling. The description of tools provided in the method would also help interdisciplinary teams discuss and select the specific analysis and design tools (these include spreadsheets, engineering reports, power system data, and simulation software, among others). The process followed in this work could also guide future research requiring models of the existing power systems under similar conditions and analyzing DER impacts (especially PV systems) on grid operation.

5. Conclusions

The paper shows the integrative/holistic process in building a model of a power system for the study of high penetration of distributed PV. Planning and social considerations are included in creating a realistic demand profile from census data and socio-economic sectors indicators. Although obtaining most data to model the entire system was a difficult task, public sources, reasonable assumptions considering historical data, and previous studies were used in order to get the best results possible. Furthermore, residential rooftop areas were selected as a feasible design option for PV system without occupying limited land resources. This selection aligns with the social and environmental preferences of most citizens in Puerto Rico. Finally, PV systems' potential electricity production installed on rooftops was calculated using residential rooftop area data and the insolation obtained for municipalities.

Results showed that Puerto Rico and other tropical and subtropical islands have an excellent opportunity to increase renewable energy, especially distributed energy resources close to demand centers. DPV systems can also improve the response during emergencies by enabling the power system to be divided into mini regions that use local energy resources. The methodology presented in this paper can assist in analyzing the effects of the potential DPV systems production and suggesting power grid designs that mitigate DPV impacts on bulk power systems in remote and islanded systems. The model can also be used to study the interplay of transmission and distribution systems in order to design topologies that maximize the use of distributed and renewable energy sources. Studying this interplay is vital for an energy transition to achieve a balance between the large-scale transmission network and the smaller scale distribution systems with a high penetration of renewables.

The integrative engineering-social perspective in developing the model and the actions to manage data limitations are aspects that could be followed by others seeking a more holistic view of power infrastructure analysis. This integrative work is of particular importance and applicability in locations with aggressive renewable energy goals (e.g., 50 or 100% renewable energy), and where utility data are not readily available. The case study of Puerto Rico shows the capabilities of the method, while the distributed PV results present lessons for islanded and remote, rural systems with low inertia. On the other hand, a model like this one can be used to study the new role of large generators in supporting an increased use of distributed energy resources, and in some cases, a transition to a renewable-dominated power system. Tropical and subtropical regions of the world will find this paper useful, since most likely those places have similar insolation levels as the case study presented. Literature on the integration of renewable energy to the grid is dominated by studies of regions within large, interconnected power systems. However, comprehensive engineering work with social considerations that is related to isolated/islanded and remote locations is very limited. Thus, the comprehensive power system model and the method to produce it will also benefit electric energy planning on islanded and remote locations.

Finally, as future work, the model will be used by engineers and social scientists in crafting and analyzing plausible scenarios of renewable energy integration in a low-inertia power system. The holistic transmission-distribution model presented in this paper can also be used to address the challenges related to the electrification of transportation. Electric vehicles are expected to increase the energy use (load) at the distribution level, thus effective, integrated transmission-distribution models are needed. Through those integrated studies, electricity would be enabling a sustainable energy transition at all levels: generation, transmission, distribution, and load.

Nomenclature

ARRA	Available Residential Rooftop Area (m^2)
BPS	Bulk power system
DAI	Daily Average Irradiance per year ($kWh/m^2/day$)
DER	Distributed energy resources
DPEI	Daily Potential Energy obtained by Insolation on the terrestrial surface (kWh/day)
DPEP	Daily Potential Electricity Production by PV systems (kWh/day)
DPV	Distributed PV
GT	Gas turbine
IRP	Integrated Resource Plan
NREL	National Renewable Energy Laboratory
PREPA	Puerto Rico Electric Power Authority
PV	Photovoltaic
SAM	System Advisory Model
ST	Steam turbine

STC	Standard testing conditions
TC	Transmission center
TC	Operating PV module temperature (°C)
TCη	Temperature coefficient (%/°C)
TN	Operating PV module at Standard Test Conditions (25 °C)
η_{inv}	Inverter efficiency
η_{loss}	Efficiency for losses
η_{rated}	PV module efficiency

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