Grid Adequacy and Cooperation in Central America: A Data-driven Analysis

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Abstract**—** Central America has the highest penetration of non-hydro renewable energy in the Western hemisphere. Grid adequacy evaluations are critical for such countries due to accelerating demand growth, constrained financial resources, and the inherent variability of renewables. A regional interconnection (SIEPAC) was constructed in the region to allow cooperation and coordination between national grids. This study calculates the Loss of Load Expectation (LOLE) and Effective Load Carrying Capacities (ELCC) for three countries connected to SIEPAC (Nicaragua, Costa Rica, and Panama) for years 2013-2015. The results show that Costa Rica and Panama have significant excess capacities deriving mostly from hydropower. Further, results show that regional excess capacity sharing would allow Nicaragua to reduce its thermal capacity while maintaining an acceptable LOLE. Specifically, at current capacity levels and expected demand growth, Nicaragua in 2015 only required 31% of its thermal capacity and would not require its full thermal capacity until 2025.

Index Terms**— Loss of Load Expectation, Effective Load Carrying Capacity, Central America, Grid Adequacy**

I. Introduction

Grid adequacy is a measurement of the ability of electric systems to supply aggregate demand at all times while taking into account scheduled and un-scheduled power outages [1]. Grid adequacy is an important measure for both short-term operations and long-term planning, allowing operators to evaluate the risk of load-shedding due to insufficient reserves with the cost of maintaining unused generators. Measurements of grid adequacy that were defined in the early stages of electricity grid development are still in use today, such as loss-of-load expectation (LOLE) and effective load carrying capacity (ELCC) [2]. LOLE is an expected amount of time in which peak load will not be met over the course of the study period. ELCC is the MW contribution of an individual or group of generators towards reducing LOLE.

Larger, interconnected systems have some of the most stringent standards for LOLE. For example, the National Electric Reliability Corporation (NERC), which regulates much of North America (8 regional reliability entities), requires a “1-in-10” threshold for LOLE, meaning that the LOLE should be less than 0.1 days/year (which can also be interpreted as 2.4 hours/year). In Europe, LOLE standards differ by country: France and Belgium require a maximum of 3 hours/year, while Ireland and Portugal require a maximum of 8 hours/year [3].

Central America is a particularly interesting region to study with regards to current and future grid adequacy as it is at the global forefront of renewable energy integration efforts [4]. The region has the highest penetration of non-large hydro renewable energy sources (with an installed capacity of 30%) in the Western Hemisphere (14% regional average) [5] [6] [7]. Moreover, the region includes countries that are leading global renewable energy integration efforts relative to their income such as Costa Rica (non large hydro renewables: 35% of total generation in 2015) and lesser known cases, such as Nicaragua, whose recent fuel-switching efforts have exceeded those of much larger economies in the region [4].

With a new regional interconnection (2013) connecting six different countries, the Central American Electrical Interconnection System (SIEPAC) is in a region that has continuously struggled to balance reserve costs while meeting demand. The challenge is even greater as the SIEPAC interconnection not only tries to increase the grid’s reliability, but also seeks to create a competitive market in the region and attract foreign investment in power generation and transmission to Central America.

While there are no existing regional studies on what a larger interconnection will do to grid adequacy or renewable energy integration efforts, there are country specific studies that have begun demonstrating that a greater interconnection is the most cost-effective strategy for increasing the amount of solar and wind energy in the regional power generation mix [4]. Penetration of non-hydro renewable energy is also expected to continue growing rapidly in the future: Honduras currently produces 26% of its generation from wind and solar [8], El Salvador is currently engaging in a licitation process for 170 MW of wind and solar developments (it expects to produce 33% of its total generation from non-hydro renewable energy by 2018) [9], Guatemala has recently installed 63 MW of solar [10] and launched a licitation process for over 250 MW of wind and solar by the end of 2017 [11], and Panama hopes to produce 70% of its generation from renewable energy by 2050 [12]. This increasing penetration of uncertain and variable renewables energy necessitates the urgent development of currently non-existent public grid adequacy studies.

Based on publically available data [13] [14] [15], this study conducts a grid adequacy analysis on three of the countries in the SIEPAC network: Nicaragua, Costa Rica, and Panama. The study is done retroactively using historical data from 2013-2015 in order to gain a more accurate understanding of how changes in renewable penetration coupled with electricity demand growth may have impacted grid adequacy over the last 3 years. Further, this study explores the possibility of further leveraging the regional interconnections in order to reduce regional reliance on thermal generation in the region, specifically in Nicaragua where 51% of electric energy generation in 2015 was derived from fossil fuel sources. Reducing the need for thermal plants will accelerate regional progress towards renewable energy goals and reduce regional dependence on imported fossil fuels.

Section II provides a summary of the three electricity grids under study. Section III details a methodology of both deterministic and probabilistic methods for measuring grid adequacy, as well as describes a means for evaluating the impact of greater regional cooperation. Section IV shows the results of the grid adequacy analysis conducted for Nicaragua, Costa Rica, and Panama, as well as the possible reduction in fossil fuel generation in Nicaragua assuming greater capacity sharing between the countries. Section V discusses the results, Section VI offers opportunities for future work, and Section VII concludes the paper.

II. Electricity Grids in Nicaragua, Panama, and Costa Rica

Nicaragua is the 2nd poorest country in the Western Hemisphere [16], and yet it is expected to reach an unprecedented level of 90% renewable energy resources by 2020 [4]. Nicaragua is planning to achieve this goal using a diverse set of renewable resources and integration strategies [4]. The country of Nicaragua is situated in a region where it contains vast wind [17], solar, and geothermal [18] potential. There were 22 MW of wind added to the Nicaraguan national grid in December of 2013 which brought the total rated capacity to 186.6 MW. In 2015, Nicaragua generated 4.3 TWh and had a peak demand of 665 MW.

Costa Rica has the second most-developed electricity and telephone infrastructure in Latin America according to the World Economic Forum Global Competitiveness Index [19]. Costa Rica is also a leader in renewable generation, primarily through the use of large hydropower plants. In 2015, the country was able to power its grid without fossil fuels for 285 days, sourcing 99% of generated electrical energy from renewable sources [20]. Costa Rica added 1 MW of solar capacity in 2014, which yielded 0.01% of generation in both 2014 and 2015. Costa Rica generated 10.7 TWh in 2015 and had a peak demand of 1619 MW in that year.

The energy portfolio of Panama closely resembles Costa Rica, with large hydropower plants serving as the primary source of generation. Panama has the largest penetration of solar out of the three countries studied, with an initial installation of 2.4 MW in February 2014 that was then supplemented by an additional 48.5 MW in 2015, supplying 1% of generation for that year. Panama is also the only country with coal generation out of the three countries studied, with 120 MW added in February of 2014. Coal is categorized as thermal generation in this study. In 2015, Panama generated 9.7 TWh and had a peak demand of 1635 MW.

Fig. 1 provides a summary of the generation and capacity by type of the three grids over the study period as a percentage of the total generation amongst all three countries. Solar generation is not shown below as it is only of a measurable percentage in Panama, as previously discussed.

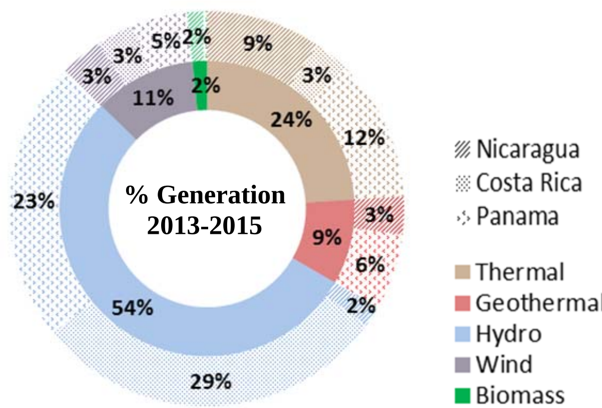

FIGURE I: GENERATION BY TYPE ACROSS PANAMA, COSTA RICA, AND NICARAGUA (2013-2015)

III. Methodology

The dataset used in this analysis combines hourly demand and generation data for each country over the years 2013-2015; also included are the rated capacity, maintenance schedules, and unplanned outages for each unit [13] [14] [15]. Where data is available, the actual planned and unplanned outages are used; otherwise these outages are estimated based on schedules for that grid from available years. Data was stored in a PostgreSQL database on an Ubuntu 16.04 server and a program written in the Python programming language was used for analysis.

The next section describes the process used to solve for grid adequacy probabilistically using the loss-of-load expectation (LOLE).

A. Calculating Grid Adequacy: LOLE

The probabilistic analysis for grid adequacy requires knowledge of the following concepts: reliability functions, loss-of-load probability (LOLP), loss-of-load expectation (LOLE) and effective load carrying capacity (ELCC).

The reliability function $R(g)$ - also referred to as empirical complementary cumulative distribution function or survival function - represents various states g of the system (levels of available generation, reported in MW) and the probability that there is less than *g* MW of available capacity for any given time. The reliability function is determined by first calculating the potential capacity time series PC(*t*), which is the rated capacity of a plant after it has been commissioned and 0 otherwise, and *t* is an hour within the study period. The maintenance schedules and outage reports are then used to subtract unavailable capacity from each plant, leaving an available capacity time series AC(*t*). D(*t*) represents the MW of demand at time *t*. C_i is the rated capacity of generator type *i*, and $O_i(t)$ is the MWs of plant outage at time *t* for each *i*. $B_i(t)$ represents a binary variable indicating whether *i* has been built.

$$PC_i(t) = B_i(t) * C_i \tag{1}$$
$$AC(t) = PC_i(t) - O_i(t) \tag{2}$$

From this available capacity time series, a complementary cumulative distribution function is calculated by sorting the values in AC(*t*) from (2) in ascending order and assigning a probability to each value *g* by counting the instances of values less than *g* in AC(*t*). Assigning probabilities to each unique value in AC(*t*) generates a complementary cumulative probability function that represents the probability that less than *g* MW will be available at any given time. Evaluating this function for each value in D(*t*) provides the loss-of-load probability LOLP(*t*), which is the probability that there is not enough available capacity to meet demand at time *t*.

$$LOLP(t) = R_{D(t)}(g) = P(D(t) > g) \tag{3}$$

With LOLP determined, there are a variety of methods to calculate LOLE over the study period. LOLE is defined according to Requirement R1.1 of NERC Standard BAL-502-RFC-02 [21]. LOLE is the sum of the loss of load probabilities at the peak hour of each day, for each year in the study period. The effective load carrying capacity (ELCC) of each generator type is also calculated in this study. $ELCC_i$ is a constant value in MW that is added to the existing reliability function after all capacity from generator type *i* has been removed in order to maintain the same LOLE [22] [23].

This study follows the method for managing variable generation such as wind in grid adequacy calculations developed by the NERC Variable Generation Task Force [24] and IEEE PES Task Force on the Capacity Value of Wind Power [25], where variable generation is considered as a negative load, leading to the use of a net demand time series for D(*t*). The ELCC of variable generation is then measured by removing the generators from the net demand time series rather than the reliability function and then adding constant values in MW until the LOLE reaches its initial value.

In addition to calculating ELCC of generator types, a similar calculation is performed in order to determine the effective excess capacity (EEC) of the system beyond the "1-in-10" standard. D(*t*) is adjusted by a constant number of MW until it meets the standard. This quantity represents the effective excess (or lacking) capacity necessary to maintain this standard. It can also be interpreted as the additional (or lesser) demand in MW that the system could handle while maintaining an acceptable grid adequacy (LOLE=0.1).

B. *Impacts of Cooperation*

This study also explores the theoretical impact of greater grid cooperation on the ability for thermal plants to be decommissioned while maintaining acceptable levels of grid adequacy. This calculation will focus on reducing thermal generation in Nicaragua since approximately 50% of generation comes from thermal generation. LOLE will be recalculated for Nicaragua except with only partial amounts of the total thermal capacity made available. Instead, the effective excess capacity from the other countries in the study will be assumed to be available to Nicaragua through the SIEPAC interconnection. By only making the effective excess capacity available to Nicaragua, it will ensure that all three countries would still be able to achieve a LOLE of 0.1. It is understood that additional transmission, regulatory, and political constraints further limit the ability for cooperation but they are outside the scope of this study.

Transmission constraints along the SIEPAC line will be used to further limit the amount of available capacity Nicaragua can utilize from Costa Rica and Panama. Currently, the maximum capacity of the SIEPAC line is 300 MW, but there are plans for expansion to 600 MW, so this calculation will be repeated for each possibility. Following a similar method to Section III.A, the available capacity time series AC(*t*) will first be calculated as seen in (4). The current ($c_{SEIPAC} = 300$ MW) and future ($c_{SEIPAC} = 600$ MW) transmission constraint of the SIEPAC line are applied in order to calculate an estimate of the additional capacity available to Nicaragua. Additionally, varying percentages (X=0 to 100%) of the total thermal capacity are used in the available capacity calculation shown in (4). Each of these available capacity time series are then used to calculate LOLE values. These calculations show the impact on LOLE when regional available capacity (sourced largely from hydropower) is made available while simultaneously taking some of Nicaragua's thermal capacity offline.

$$\begin{aligned} AC_{N'}(t) = {} & AC_{NICA,non-thermal}(t) \\ & + Max(C_{SEIPAC}, EEC_C + EEC_P) \\ & + X * AC_{NICA,thermal}(t) \end{aligned} \tag{4}$$

For example, lets say that (4) is used to calculate the available capacity with X=20%. The reliability function is calculated and subsequently evaluated for each net demand value in the time series according to (3). The LOLE is then calculated as previously explained. This LOLE represents the grid adequacy if only 20 % of Nicaragua's thermal capacity was made available to the system and the rest was taken offline. This calculation is repeated for X=0-100% in 1% intervals. In addition to calculating LOLE for 2013-2015, values are calculated for future years assuming consistent demand growth of 5% per year.

IV. Results

Table 1 summarizes the results of the LOLE calculations, including the effective excess capacity (EEC) beyond what is required for the "1-in-10" standard. Fig. 2 shows the ELCC of each type of generation. Under the existing operating conditions, a LOLE of 0 is calculated for each year for each country, with the exception of Nicaragua in 2013 (LOLE=0.06) as shown in Table 1. This led to values of 0 for several ELCC types, as their contributions to LOLE were masked by the excess capacity in the system. In order to more accurately evaluate the effective load carrying capacity of units, the ELCC was measured after removing the effective excess capacity, and calculating the load carrying capacity for an LOLE of 0.1.

TABLE I: GRID ADEQUACY RESULTS

Grid Adequacy By Year	Nicaragua		Costa Rica		Panama	
	LOLE (days/ year)	*EEC (MW)*	*LOLE (days/ year)*	*EEC (MW)*	*LOLE (days/ year)*	*EEC (MW)*
2013	0.06	23	0	420	0	191
2014	0	103	0	532	0	253
2015	0	91	0	580	0	646

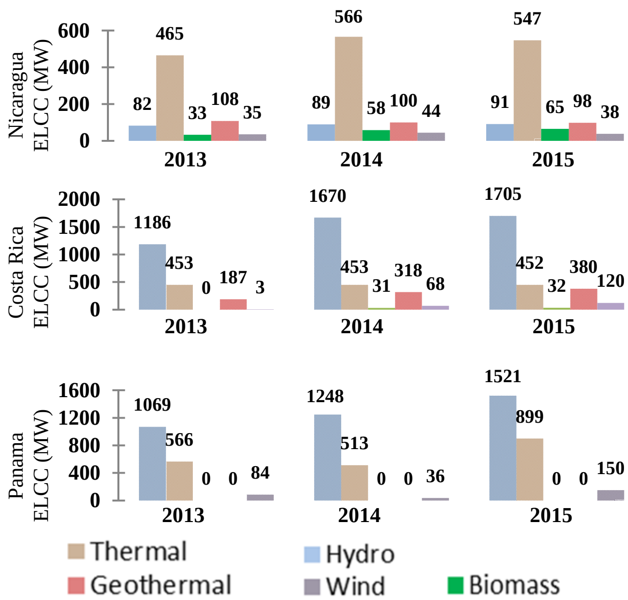

FIGURE II: EFFECTIVE LOAD CARRYING CAPACITY BY YEAR

Fig. 3 and Fig. 4 show the relationship between LOLE and a percentage of total thermal capacity made available in Nicaragua for a variety of years. The solid lines represent actual data (2013-2015), while the dotted lines represent predicted years with 5% yearly demand growth. Where each line meets the horizontal line at 0.1 indicates what percent of the total available thermal capacity was necessary to meet the "1-in-10" standard. Fig. 3 does not display years after 2025, as a LOLE of 0.1 can not be achieved in these years even with full thermal capacity. Fig. 4 does not show years before 2020 as these years achieve a LOLE of 0 even with no thermal capacity made available in the country.

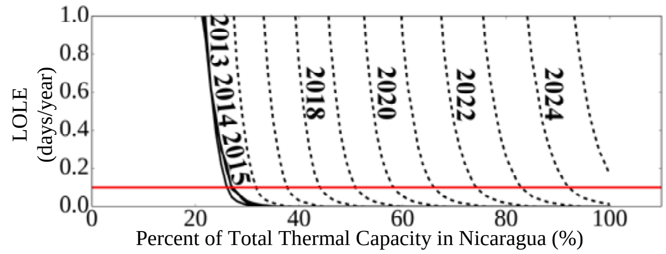

FIGURE III: NICARAGUA LOLE WITH REGIONAL CAPACITY (300 MW CONSTRAINT) AND REDUCED THERMAL CAPACITY

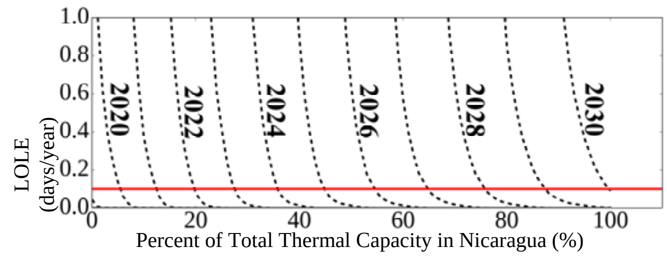

FIGURE IV: NICARAGUA LOLE WITH REGIONAL CAPACITY (600 MW CONSTRAINT) AND REDUCED THERMAL CAPACITY

V. Discussion

As mentioned in the results, only one country (Nicaragua) and one year (2013) recorded a non-zero LOLE value. This indicates that there is excess capacity on the grid in all three countries. Expected increases in electrification rates, coupled with economic development, would increase demand in the coming years and justify the current excess capacity. This case can be made most strongly for Nicaragua, which currently has the lowest electrification rates in the region (77.9%) [26] and the lowest effective excess capacities each year (23, 103, and 91) MW. If demand in Nicaragua continues to grow at a 5% rate, the grid will no longer have effective excess capacity (and violate the NERC "1-in-10" LOLE standard) within 3 years. The increase in effective excess capacities between 2013-2015 of Costa (420 to 580 (38%)) and Panama (191 to 646 (238%)) exceeded their respective growths in demand (13% and 6%) and assuming similar projected growth, would reach the NERC LOLE standard of 0.1 days/year in approximately 3 and 6 years, respectively. These calculations do not take into account additional planned capacity, which would further extend these timelines. Nicaragua plans on building an additional 500 MW by 2030 [27], Costa Rica has plans to reach nearly 5 GW of capacity by 2030 [28] and Panama plans on reaching about 12 GW by 2050 [29].

Fig. 2 indicates that Nicaragua receives a vast amount of its grid adequacy from thermal generation as indicated by relatively high ELCC values, where Costa Rica and Panama rely more heavily on hydropower. Thus, the study analyzes the impact of greater regional cooperation in reducing Nicaragua's use of thermal generation while maintaining grid adequacy. This reduction in thermal capacity would assist Nicaragua in reaching its long-term energy goals of 90% renewable by 2020 [4]. Fig. 3 indicates that Nicaragua could have used only 30 % of their overall thermal capacity in 2013, 32% in 2014, and 31% in 2015. Further, even without additional capacity built, Nicaragua would not require its full thermal capacity to maintain the NERC grid adequacy standard of 0.1 until 2025 with the given transmission constraint of 300 MW. When considering the SEIPAC expansion to 600 MW as illustrated in Fig. 4, Nicaragua would not require its full thermal capacity until 2030. These results indicate that greater use of the interconnection, and greater cooperation between dispatch centers, could accelerate progress towards renewable energy goals and reducing regional dependence on imported fossil fuels.

VI. Future Work

Future work will incorporate additional countries along the SEIPAC network, specifically Guatemala, El Salvador, and Honduras. Planned capacity and more restrictive transmission constraints will also be integrated into the study in order to provide a better sense of how greater cooperation would affect grid adequacy in future years. The economic implications of cooperation given the regional market, as well as the environmental implications (reduced local air pollution and global CO2 emissions) will also be considered.

VII. Conclusion

This paper calculated the loss-of-load expectations for three electricity grids along the SEIPAC line in Central America: Nicaragua, Costa Rica, and Panama. Results indicated that in all three cases, the grids carry excess capacity beyond what would be sufficient to meet NERC standards. While this additional capacity is less important as long as electrification rates and demand continue to increase, operators still incur additional cost by holding these resources unnecessarily. Results of this study show significant opportunity for the sharing of additional capacity. Specifically, the additional capacity from renewable sources (large hydropower) in Costa Rica and Panama could offset the additional capacity in Nicaragua that derives mostly from thermal generation, thus reducing the regions overall reliance on fossil fuels for electricity generation. As climate change impacts continue to affect the globe it is important for countries to cooperate wherever possible to reduce their impact.

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