Beyond Oil: The Transition to a Low-Carbon Grid in Nicaragua

by

Diego Ponce de León Barido

Submitted in partial satisfaction of the requirements for the degree of:

Masters of Science
In the
Energy and Resources Group
University of California, Berkeley

Approved: Daniel M. Kammen May 8, 2014
Date

Daniel M. Kammen
Professor, Energy and Resources Group
University of California, Berkeley

Approved: May 8 2014
Date

Faculty Two
Assistant Professor, Energy and Resources Group
University of California, Berkeley

Received By: May 8, 2014
Date

Kay Burns
Graduate Student Affairs Officer, Energy and Resources Group
University of California, Berkeley

Abstract

In the last decade, and especially within the last few years, several countries and regions around world have demonstrated that renewable energy is fundamentally a choice, and not a foregone conclusion.[1] Energy technology choices are now not only decided by their cost-effectiveness, but are now primarily motivated by national and energy security issues, industrial development, financial risk mitigation, and the need for grid flexibility and resilience. This is the case of Nicaragua, which after a history of foreign intervention in its state affairs and electricity sector currently finds itself at the cusp of energy independence and of transitioning to a low-carbon energy system. Here we use SWITCH (a loose acronym for Solar, Wind, Hydro and Conventional generation and Transmission Investment) to model and optimize the capacity expansion of renewable and conventional generation technologies, storage technologies, and the transmission system while explicitly accounting for the hourly variability of intermittent renewable energy for four investment periods between 2013 and 2030. During the final investment time period (2026-2029) our results suggest that Nicaragua could only use 4% of bunker fuel oil generation for meeting total national demand (wind 21%, biomass 6%, and geothermal 10%), with hydropower (reservoir and run of river) providing the bulk of the generation (~59%). Future iterations will explore greater system flexibility, including allowing power flow across the SIEPAC interconnection transmission line, enabling grid-tied storage, and allowing geothermal and biomass generators the ability to provide ancillary services (spinning and quick start reserve capacity). We expect the latter to significantly reduce system costs.

Index

“Ten years from now, twenty years from now, oil will bring us ruin.
It is the devil's excrement.
We are drowning in the devil's excrement.”

Juan Pablo Perez Alfonso (Venezuela), OPEC’s Founder and 1st Head, 1976.

1. Introduction

In the last decade, and especially within the last few years, several countries and regions around world have demonstrated that renewable energy is fundamentally a choice, and not a foregone conclusion.[1] Energy technology choices are now not only decided by their cost-effectiveness, but are now primarily motivated by national and energy security issues, industrial development, financial risk mitigation, and the need for grid flexibility and resilience.[1] During 2012, wind power generation in China increased more than generation from coal, renewables accounted for almost 70% of all capacity additions in the European Union, Germany met 23% of national demand with renewables, and the United States added more capacity from wind power than any other technology.[2] In Latin America and the Caribbean (LAC) renewable capacity grew from 11.3 GW in 2006 to 26.6GW in 2012, and in that year alone LAC brought 3.3GW of new renewable energy capacity online.[3]

This new decision-making process has also been accompanied by investment. Although global annual renewables investment went down by 12% from a record year in 2011, the amount ($US244 billion) was still the second highest and 8% higher than 2010.[2] While commitment to renewable energy has become relatively uncertain in Europe and the United States (29% drop from 2009 levels), the balance and interest in renewable energy has decisively shifted towards emerging economies with a $US112 billion investment in 2012 (46% of the world total), and 34% higher than the previous year.[2] In Latin America, Brazil and Nicaragua have shown to be the most promising countries for low-carbon energy investment in the Western Hemisphere primarily because of their enabling frameworks (policies, market structure and online clean energy capacity), financing, and investment patterns.[3] While 55% of the investment in clean energy still goes to Brazil, smaller, relatively more progressive economies such as those found in Nicaragua and Uruguay (economies 0.3% and 2% the size of Brazil) have been making great progress towards achieving low-carbon energy independence.[3]

Nicaragua is perhaps the most interesting case in the Western Hemisphere currently undergoing a renewable energy transition. Over the last two decades, GDP and national energy consumption have grown at 4.4% and 5.7% per year,[4] and today, oil accounts for over 80% of all energy imports (energy imports >45% of total annual national demand).[4] Over 55% of Nicaragua's revenue from exports goes towards covering this expenditure.[5] This matters, because despite strong GDP growth (4.7%/year), the country still holds the 129th position in the UN's HDI, the lowest position in the Western Hemisphere after Guatemala and Haiti.[4] Nicaragua's dependence on bunker fuel oil has reduced its ability to invest and focus on other sectors of society that are crucial to the country's long term human development goals.

More recently Nicaragua has developed a vision and commitment to becoming a regional leader in renewable energy. In the last five years (2009-2014), it installed ~190MW of wind energy capacity (14% of totaled installed capacity), underwent an intensive geothermal technical capacity training in partnership with Iceland, and in 2012 received $US 292 million in new clean energy investments.[3,6] Between 2006 and 2012 the country received $1.5bn of cumulative renewable energy investment (5% of GDP), and today renewable energy (excluding large hydro) accounts for 45% of the country's total installed capacity.[7]

Yet, despite this great progress, the country's ambitious goals (79% and 93% renewables by 2017 and 2026 respectively) seem daunting. Although at the end of 2013 renewable energy generation represented 45% of the total, new capacity and investments would have to grow steadily at 11% per annum to reach the 79% target, and at 4% per year to reach the 2026 target.[8] Although reaching these targets is by no means unfathomable, this future will require grid investments, the cost-effective management of intermittent renewables, and fully taking advantage of all the country's renewable resources. Equally important is that the planning process is accompanied by an understanding of the resources that might be affected by climate change, that it shows respect and commitment towards protected areas, and that people's land rights are respected.

Here we provide an in depth analysis of the different resources that compose Nicaragua's electricity landscape covering both a resource's potential and its inherent variability, as well as its societal dimension. We also use SWITCH (a loose acronym for Solar, Wind, Hydro, and Conventional generation and Transmission Investment) to understand how Nicaragua's renewable energy resources could be optimally integrated into the grid.[9,10,11] This is the first regional study (including Mexico and Central America) to investigate the optimal integration of large-scale renewable resources, as well as the first to consider large-scale solar generation (rooftop PV and central generation).

1.1 Background: A History of Intervention and Dependence

Historically, political and foreign interests that created the 'legacy grid' and shaped the country's energy landscape have heavily influenced Nicaragua. The U.S backed Somoza political dynasty (1936-1979) treated Nicaragua as a feudal economy with all of its power and the majority of the infrastructure (including the electric power grid) focused on Managua, while profiting from resource extraction (coffee, cotton, beef and other animal byproducts) in the rest of the country.[12] During the early 60's and 70's, ESSO, Shell, Chevron and several other multinational oil companies performed offshore seismic surveys and drilled exploration wells in the pacific coast without any of this ventures proving fruitful.[12] Shortly after the 1972 earthquake that killed over 6,000 people, displaced over 300,000 and devastated the capital city's infrastructure, the Frente Sandinista de Liberacion Nacional (FSLN) took over the country (1979).[12]

Although the Sandinista regime increased efforts towards energy independence (in 1981 three active geothermal wells at Momotombo were producing 18 MW each with the help of Italian and Canadian aid agencies) the country was still very much dependent on foreign oil. Mexico and Venezuela, in an attempt to fill a power vacuum left by the United States, quickly began asserting themselves as powerful oil players in the country.[12] The Mexican government supplied 7,500 oil barrels a day, supported the development of the country's hydrocarbon infrastructure, and donated two geothermal well-drilling rigs in exchange for coffee, hides, meats, and sugar.[12] Similarly, the Venezuelan government, which had previously arranged highly favorable oil terms with the Somoza regime (1974 Puerto Ordaz Agreement), did not miss the opportunity to strike another deal and committed itself to supplying $55 million in oil to Nicaragua at low interests (4%), as well as long-term loans for industrial development at low interest (2%).[12] Nicaragua, Mexico, and Venezuela then signed the San Jose Accord (1980), which established that Nicaragua, together with other Central American and Caribbean nations, would receive oil at 70% of current market rates.[12,13] The remaining 30% could be paid over a 5-year grace period (8% interest rate), and if used for development programs, it could be paid over 20 years at even lower interest rates (6%).[12,13]

By 1985, however, Nicaragua was no longer able to make any of its San Jose Accord payments due to a chronic shortage of foreign exchange, and yet another civil war (the 'CONTRA', or counter-revolutionary war). As a result, and pressured by the United States, Mexico and Venezuela stopped their preferential oil treatment towards Nicaragua.[12,13] Although Soviet block countries replaced Mexico's and Venezuela's oil aid, providing over 90% of the country's oil supply at subsidized rates, by 1987, and close to the end of the Cold War, this support was neither economically or politically feasible.[14,15] During the Sandinista regime (1979 – 1987), the electric power grid was anything but destroyed by CONTRA armed forces as they targeted strategic infrastructure such as oil pipelines, substations, rural-electrification projects and fuel storage tanks throughout the country.[12]

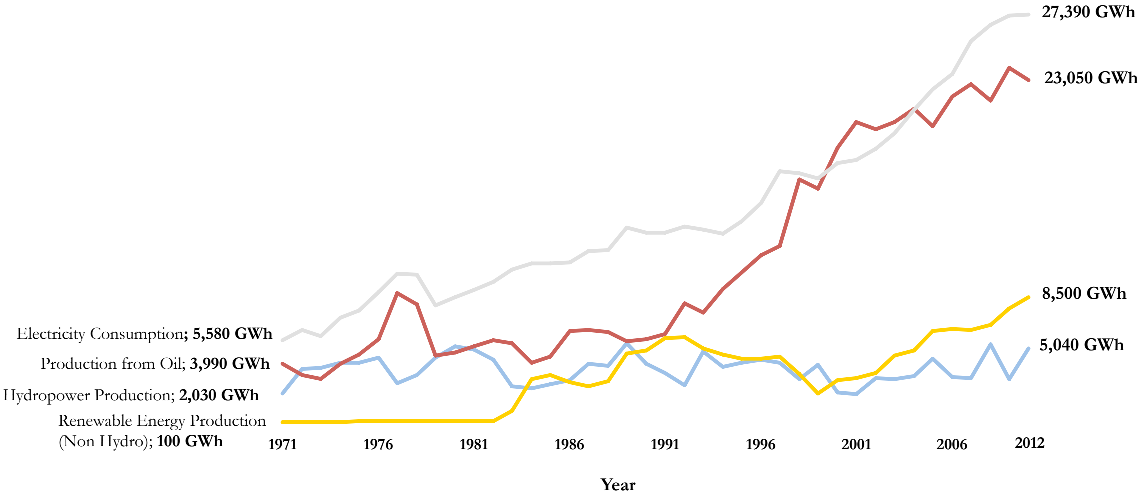


Figure 1. *Evolution of Nicaragua's Electric Power Sector (1970-2012).*[4] The sum of annual non-hydro renewable energy production (yellow), hydropower production (blue), and oil production (red) is total annual generation. Aggregate annual generation from all sources is sometimes greater than national demand due to high-energy losses (technical and non-technical losses) and energy sales to other Central American countries. Data for each year represents the previous years cumulative generation.

In 1990, the first woman head of state was elected in Nicaragua (Violeta Barrios de Chamorro, the candidate of opposition groups to the Sandinistas) and with her came the beginning of a period of economic liberalization and privatization, the end of the U.S trade embargo, and $US300 million ($US200 million were earmarked for oil and agricultural commodities) from the then Bush administration.[16] The electricity sector reforms carried out by her administration intended to ensure efficient demand coverage, to promote economic efficiency, and to attract resources for infrastructure expansion.[17] The Nicaraguan Energy Institute (INE), which had been originally created as the state enterprise to manage all aspects of the energy sector, became a regulator, and in 1992 it began negotiating contracts and concessions with private investors. At a time of historically low oil prices (1989-1999), this was a period time when funding agencies (and thus, Nicaragua's) favoritism towards oil increased even further.[18]

The 'Power Sector Reform' of 1998-99, and the current state of Nicaragua's power sector, is a direct result of the lending conditions arranged by the International Monetary Fund's (IMF) Structural Adjustment Policies (SAP's) in the country during that time.[19,20,21] Through a variety of laws, presidential decrees and regulations, this reform abolished the previous state monopoly (the Nicaraguan Electricity Company ENEL), established a bulk power market, and unbundled ENEL's assets into generation (various), distribution (then Union-Fenosa, currently DISNORTE – DISSUR) and transmission (currently ENATREL). The IMF and the World Bank also demanded the privatization of the energy generation plants through the Highly Indebted Poor Country Relief Initiative (HIPC).[22] The state oil distribution company (PETRONIC) was also transferred to the private sector under a long-term lease. During the period of time that began with president Chamorro and ended with the return of the Sandinistas (1989-2006), oil generation grew on average by 17% per year, while demand grew only by 5%/year. This period of time was marked by no investments in geothermal, hydropower, or biomass generation, as lending agencies preferred to fund bunker-fuel oil plants.

With a sharp increase in international oil prices beginning in 2002, however, the ineffectiveness of the Power Sector Reform was brought to light. INE, the state regulator, failed to approve electricity tariff increases, and thus, the financial burden of higher generation costs were passed directly to the distribution company.[19,20,21] Further aggravating the distribution company's financial burden was the fact that generators were guaranteed 'capacity payments', and thus, were paid both for their installed capacity, and for their actual generation based on a marginal price system, where prices were set by the most expensive generator.[19,20] By 2006, this system was on the verge of collapse. With rising oil prices, generators had no incentive to produce, and when they did, the costs were passed on to the distribution company, which already was suffering significant financial, technical, and non-technical (power theft) losses. By the end of the year the country was suffering from 4-12 hour blackouts that would affect the entire country on a daily basis.[19,20]

In 2006, and with the country in yet another energy crisis, Daniel Ortega and the Sandinistas came back to power. Prior to his election, Ortega had arranged an oil aid package with Hugo Chavez and Venezuela that included the delivery of a 60MW bunker fuel oil plant and the inclusion of Nicaragua into the Boliviaran Alternative to the Americas (ALBA) and Petrocaribe agreements.[23] Petrocaribe, just like the San Jose accord did in the 1970's -80's, provides subsidized oil to participating countries at low interest rates.[24] Petroleos de Venezuela (PVDSA) sells crude oil and oil products on credit, and recipient countries have up to 25 years to pay back, with a 2% interest rate if a barrel is priced under $40 dollars and 1% if it is priced higher.[24] Other conditions include payment options for member countries consisting in 5% to 50% of oil costs, with grace periods of up to two years as well as short-term payments of up to 90 days. In terms of power generation, and despite Venezuela's own woes on this matter, Nicaragua has received the largest amount of aid geared towards building generation plants, as well as the development of a Venezuelan-Nicaraguan mixed enterprise (Albanisa) for power generation.[24] With Hugo Chavez' recent death, and Venezuela being immersed deep in political turmoil, the future of preferential oil diplomacy treatment towards Nicaragua seems uncertain.

1.2 Highlighting the Importance of a Reliable Nicaraguan Low-Carbon Grid

More recently, however, and with the country yearning energy independence from oil, Nicaragua has begun taking advantage of a new and growing market for renewable energy technologies. In 2013's 'Climatescope', a publication by the Multilateral Fund and Bloomberg Energy Finance, Nicaragua ranked as the third most promising country in Latin America for clean energy technologies. 'Climatescope' ranks countries according to their: 1) *enabling frameworks* (policy and regulation, clean energy penetration, price attractiveness, and market size expectation), 2) *clean energy investment and climate financing* (amount invested, funding sources, green microfinance, and cost of debt), 3) *low-carbon business and clean energy value chains* (clean energy service providers, value chains by clean energy sector, and 4) *greenhouse gas management activities* (carbon offsets, carbon policy, and corporate awareness).[3] Nicaragua placed first in the first two parameters, but performed weakly in parameters three and four.

Relative to the size of its matrix, the country has achieved the highest year-on-year growth of renewable capacity (and generation) of any other country in the Western Hemisphere.[3] By the end of 2013, the country had installed four large 40MW wind farms in the state of Rivas, and maintained steady production at their historically inefficient Geothermal production wells, while adding two new 36MW geothermal wells in the state of Leon.[8] Currently, on average, Nicaragua's annual generation mix is composed of bunker fuel oil (53%), wind (13%), geothermal (16%), biomass (6%), hydropower (11%), and imports/exports across the SIEPAC line (1%).[8] Although Nicaragua's commitment to renewables is unquestionable, its vision lacks details, obligations. and concrete measures for implementation. This is without doubt, however, a promising beginning on a new path towards a future beyond oil and energy independence.

Beyond the obvious economic benefits of a future beyond oil (improved balance of payments, foreign exchange reserves, and reduced debt, for example), there are also direct immediate benefits that a renewable energy future could bring to both the Nicaraguan people and it's natural environment.

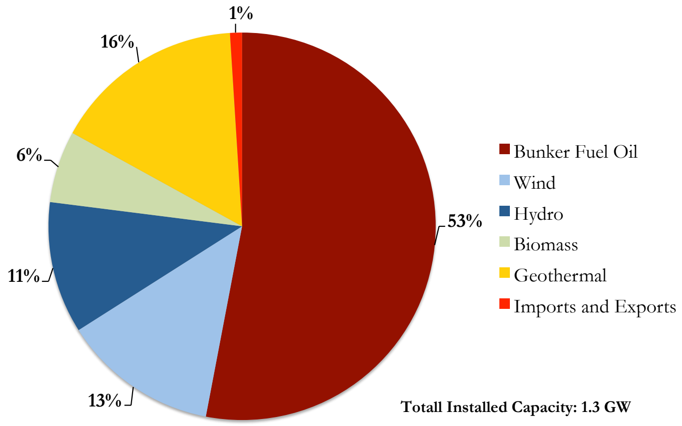


Figure 2. *Annual Average Generation by Resource in Nicaragua (2013).* Note that data for 2013 is not represented in Figure 1. The first geothermal plants were built in 1983 and 1989 (but became increasingly unproductive thereafter). Nicaragua's biomass plants were built in 1998 and 2002 respectively (total: 134 MW), and 64MW of wind were installed in 2009 and 2010. The relatively fast growth that the country has seen in wind and geothermal development since in 2012 is not represented in Figure 1.

With one of the lowest levels of electrification in all of Latin America, clean energy (centralized or decentralized) could play a large role in bringing reliable electricity services to 25% percent of the population without light.[3] Recent work in rural, off-grid Nicaragua has shown the many benefits of reliable electrification, including increased economic activity, quality of services provided (communications, security, health, and education), increased productivity, as well as an increase in leisure time due to the increased prevalence and reliability of labor saving devices. Furthermore, this work has also underscored the importance and cost-effectiveness of energy conservation measures (use of energy metering, CFL installations, more effective public lighting, for example) and the use of local and appropriate technologies (for example small-scale biomass and biogas) for rural electrification.[25]

High deforestation rates and water quality and scarcity are two other major reasons why renewable energy must have a future in Nicaragua. Although Nicaragua has recently begun efforts to curb deforestation, the country lost 21 percent of its forest cover between 1990 and 2005, and will continue losing its forests if it doesn't act with effectiveness and urgency. Agriculture and natural extraction (forestry and fisheries) have historically formed the backbone of the agricultural economy, and today they contribute close to a third of annual GDP, and roughly half of total export revenue.[4,26] It seems inevitable that as population increases the agricultural frontier will expand to protected areas of Nicaragua, such as the Bosawas reserve and Wawashang reserves. Furthermore, although agriculture plays a large role in deforestation, fuel wood for cooking by the urban and rural poor accounts for over 90% of deforestation in the country.[27] As can be seen in Figure 3 (below), in terms of energy supplied (Joules), firewood provides more energy than any other resource (imported or domestically produced) in the country; and firewood and oil together account for over 75% of total energy supplied in the country.[5] Providing renewable and reliable electricity access to urban households, as well as the urban and rural poor (full electrification), could be an important first step in attempting to curve issues related not only to deforestation but also to food security.

In Nicaragua, 80% percent of the population lives in 20% of the territory, with only 6% of the water.[26] In recent years the West side of the country, where the majority of the population lives (>80%), has begun experiencing unsustainable rates of groundwater extraction for commercial agriculture, primarily on the Pacific Coast and in the capital city of Managua.[26] The capital city's water woes are characterized by intermittency of supply, pollution to its shallow groundwater aquifers, and pollution to lake Managua, where a large proportion of the still population bathes, drinks, and fishes. Unreliable electricity provision plays a large role in water distribution intermittency, as it fails to keep pumps running and the system pressurized, increasing the system's vulnerability to leakage and pathogenic intrusion.[28]

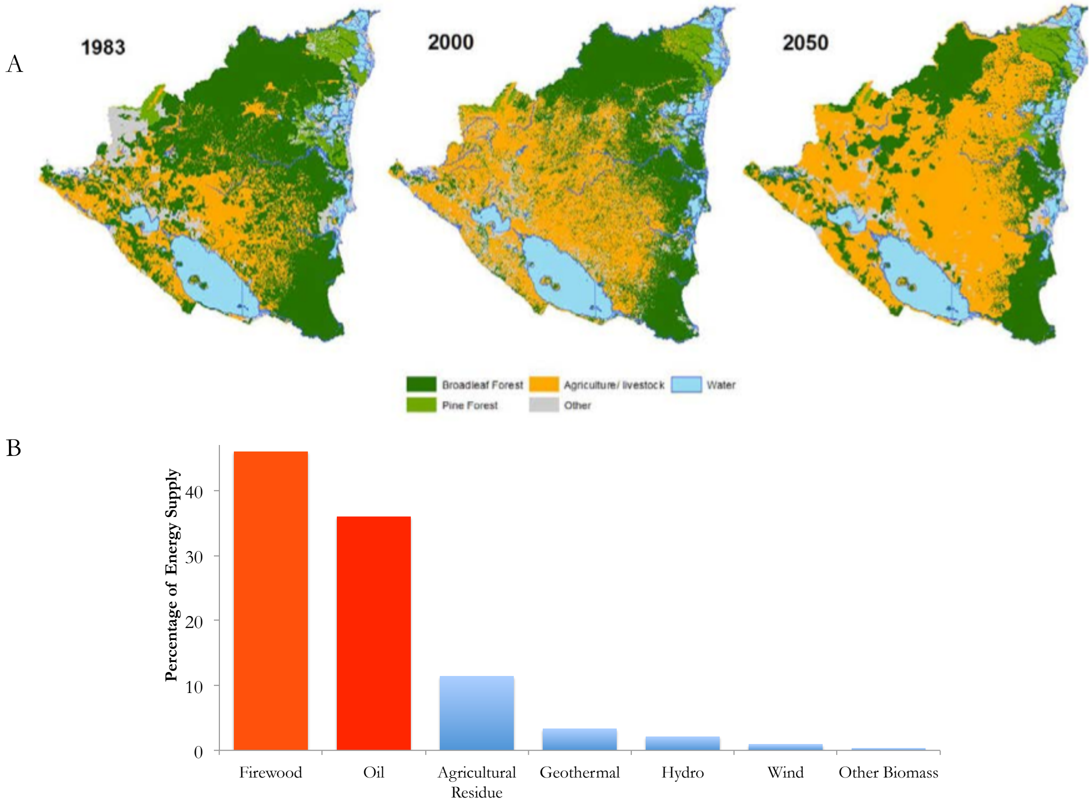


Figure 3. [A] *Land Use Change in Nicaragua (1983-2050),*[25] *and* [B] *Percentage of Total Energy Supplied by Resource (2012).*[5] Firewood and oil account for over 75% of the country's total energy consumption.

Although in 2009, a new wastewater treatment has begun treating some of the effluent that used to flow into the lake, about 25% of the city's population still uses pit latrines and septic tanks in settlements. Further compounding on the region's increasing water stress is the water-energy nexus. Given that one third of Nicaragua's bunker fuel oil plants are located in the capital city of Managua, and that on average (in the United States), thermoelectric plants can account for over 45% of total annual water withdrawals, bunker fuel generation further intensifies water scarcity issue.[29]

Two broader issues related to regional cooperation, and climate change mitigation and adaptation underscore the importance of a renewables based future. The SIEPAC line, a transmission line that will connect 37 million consumers in Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama, has the potential to: *1)* integrate a large regional market for building larger renewable generation projects (taking advantage of large spatiotemporal renewable generation variability), and *2)* increase regional competition for attracting generation project funding, thus, reinforcing incentives to develop hard goals and policy mechanisms to achieve a renewables based future.[20,30] For Nicaragua, this opportunity carries both risk and reward. If the country were to become a net electricity exporter, even when 25% of its population remains without electricity access, energy-inequality could increase even further, while at the same time improving the country's balance of payments. At the same time, a regional market threatens power sector investments as these could be redirected to neighboring countries as they seek: 1) greater renewable energy resource quality, 2) more preferable sector regulations and project approval procedures, and 3) more favorable economic incentives.[20,30] Nonetheless, SIEPAC countries will have to work together to ensure that this effort is coordinated cooperatively in order to avoid a sub-optimal benefit accruals situation resulting from countries acting in their own self-interest.

Finally, climate change impacts are no longer a looming threat but have become an immediate reality for tropical countries like Nicaragua. The future is even bleaker. Research suggests that amplification and increased frequency of extreme events (long droughts; floods) has already begun to occur in Nicaragua,[31] as well as a decrease in the number of rainy days during the monsoon.[31,32] In 2010 a combination of a deep and prolonged drought and poor water management completely closed the hydropower plant 'Las Canoas' in Nicaragua. As it is described further below, the combined impacts of deforestation and anthropogenic climate change could have disastrous consequences on Nicaragua's electric power sector. Furthermore, as the world dithers on whether to mitigate or adapt to climate change, Nicaragua will increasingly have to begin mitigating impacts, related to water scarcity, health, and food security issues. All of this will require energy, and if the country does not take advantage of its own renewable resources, not only will it be dependent on foreign oil, but also on foreign technologies in order to adapt to an increasingly uncertain future.

2. Demand and Resource Diversity in Nicaragua's Electric Power Sector

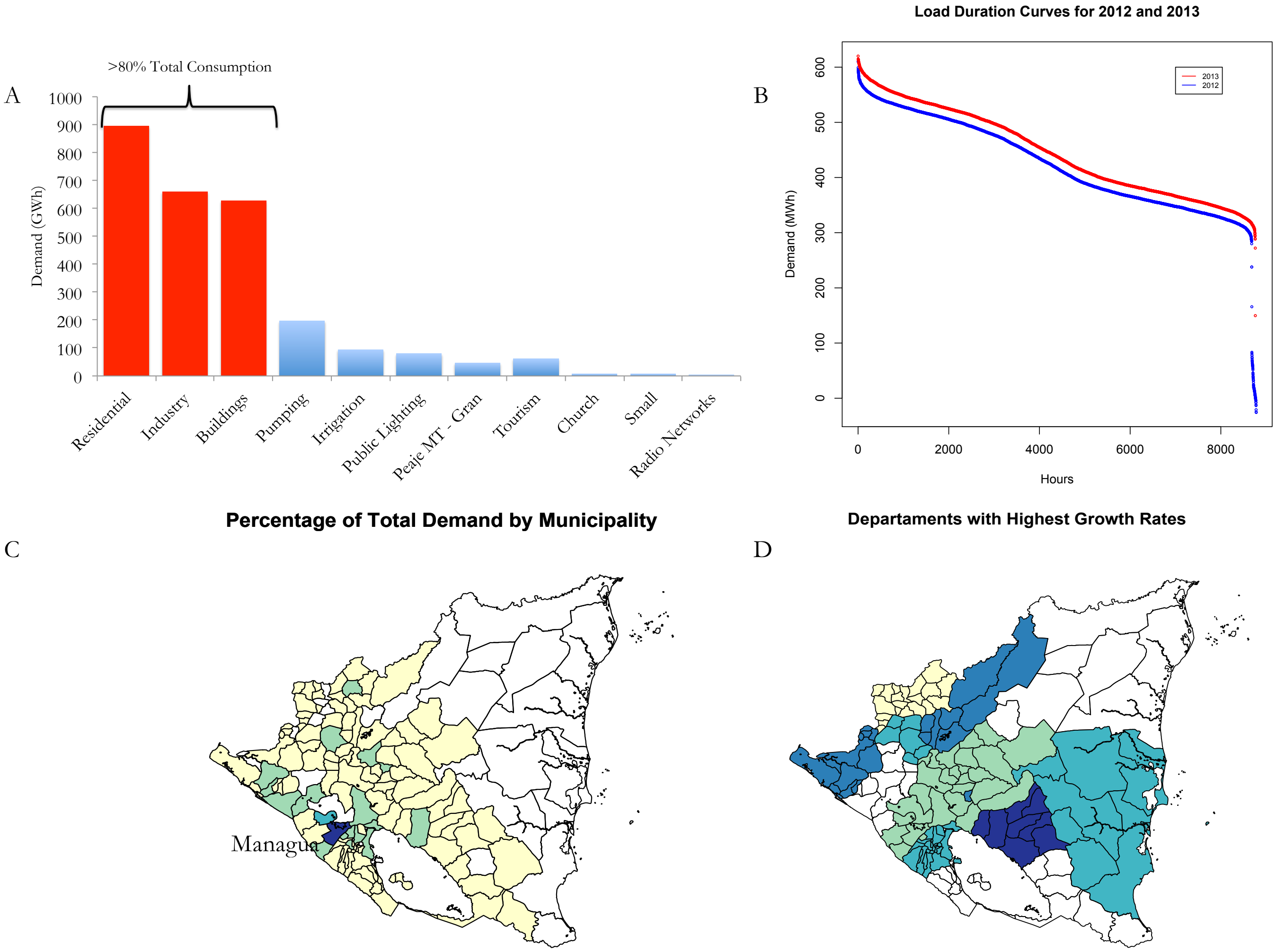
This section uses use publicly available assessments of Nicaragua's renewable resource potentials, and hourly demand and generation data (July 2011 – March 2014) to evaluate the spatial and temporal variability of Nicaragua's diverse renewable energy resource matrix. [8] We first evaluate demand growth, and then evaluate the spatio-temporal variability (annual, monthly, and daily) of all of Nicaragua's energy (for electricity) resources. We also consider the societal dimension and impacts (human and environmental) that the development of large-scale energy projects could have in the country. [33]

2.a Characterizing Electricity Demand

In Nicaragua, residential loads (33%), industrial loads (25%), and 'general loads' (23%) account for over 81% of the total load in the country.[7] Agricultural demand (irrigation), lighting, and pumping, although important for the country, still represent a very small fraction of total demand (13% of the total). The fastest growing sectors are tourism (56% per year since 2009), radio networks (33% per year since 2009), industry and manufacturing (10% per year since 2009), and residential demand (6% per year). Although these growth rates seem high, it is worth noting that these loads represent (except residential and industry) a very small fraction of Nicaragua's total energy load: radio networks and tourism represent less than 1% and 0.05% of the total load.[7] None of the energy sectors depict a temporal trend except for agriculture (irrigation), for which demand significantly drops as the summer monsoon arrives and lasts from May through November. Annual demand has been growing at six percent per year and peak demand grew two percent from 2012 to 2013.[7]

Geographically, the department (state) of Managua accounts for over half (53%) of national demand (the capital city accounts for 31%), followed by Chinandega (8%), Masaya (6%), Leon (5%) and Granada (4%). Year-to-year growth rates (2012-2013 data) are highest in Chontales (21%), Jinotega

(16%), Chinandega (15%), Carazo (13%), and Masaya (13%). Managua's year-to-year energy demand growth is relatively smaller, but still high (7%).[7]


Load Duration Curves for 2012 and 2013

Percentage of Total Demand by Municipality

Departaments with Highest Growth Rates

Figure 4. [A] *Breakdown of Total Energy Consumption in Nicaragua. Residential, industry, and building consumption account for over 80% of total national consumption,* [B] *Load Duration Curves for 2012 and 2013,* [C] *Map of Nicaragua and areas of highest demand (2013), and* [4] *Regions with the highest annual growth rates (2013-2030).*

For each hourly national dataset of 2012 and 2013 there is no statistically significant difference between summer and winter demand (ANOVA: p_2012 ≥ 0.65, p_2013 ≥ 0.73). Similarly, there is no statistically significant difference between mean demand during the warmest months of the year (March – May), and the rest of the year (p ≥ 0.43). Hourly demand data in Nicaragua is representative of a typical residential load profile curve: people wake up (6.00 – 9.00 am), they work (9.00 am – 5.00 pm) and arrive home at about 6.00 pm with maximum daily demand occurring at about 7.00 pm.[8]

2.b Baseload Generation and Non-Intermittent Renewables

2.b.i Bunker Fuel Oil

Half of Nicaragua's bunker fuel oil plants that are currently in operation were built in the 90s; the other half came online after 2006. There are currently 24 operating bunker fuel oil plants (diesel engines) with an average nominal installed capacity of 24 MWs. The country is planning to build 16 more bunker fuel oil plants (including two diesel oil, and two combined cycle gas plants) between 2014 and 2030. These plants are all located in the country's west coast and they operate both as baseload and peaking plants following load throughout the day. As can be depicted below, and given the recent high penetration of wind energy, bunker fuel oil plants compensate for drops in wind power generation during the middle of the day and increase generation to meet peak demand at night. Seasonally, oil generation presents a negative correlation with wind (April – October). As wind reduces its strength during the rainy season, oil generation is increased to compensate for increased seasonal variability, baseload, and peak demand.

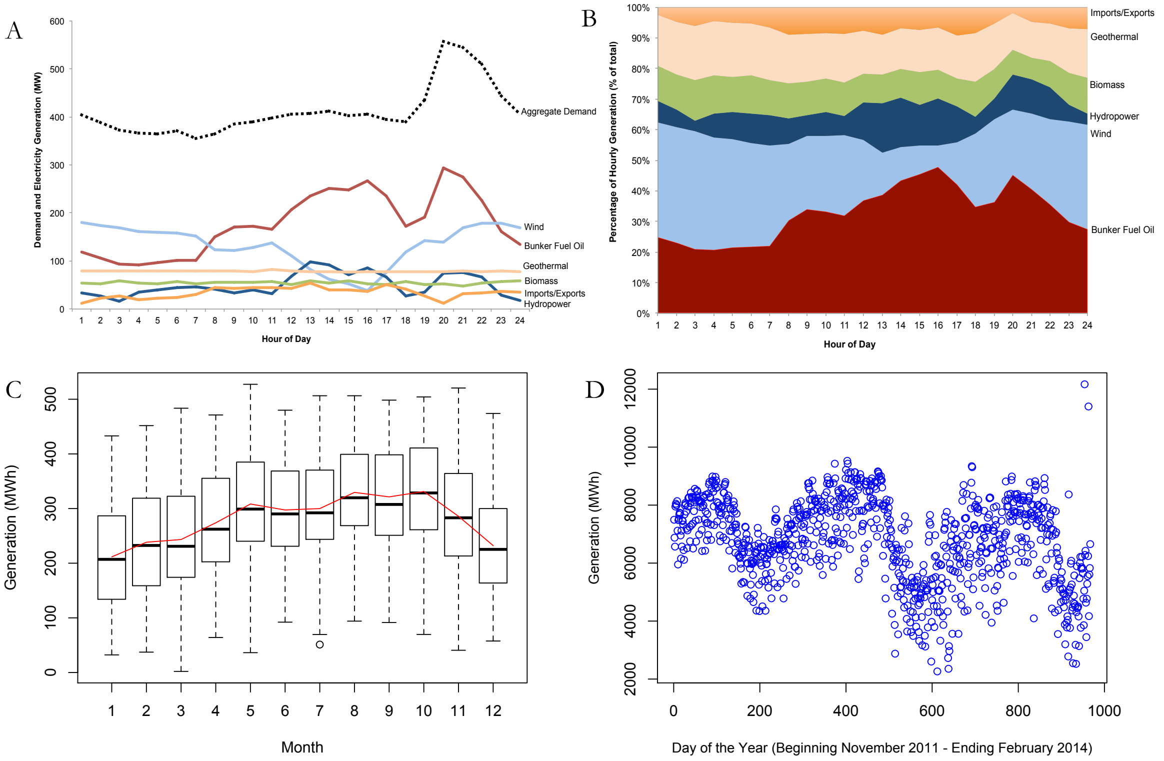


Figure 5. *Bunker Fuel Oil Generation in Nicaragua.* Although bunker fuel oil plants are used as baseload and peaking plants, generation still depicts monthly temporal variability. Historically, bunker fuel oil plants have helped manage hydrological (hydropower) variability and more recently they help alleviate both monthly and hourly variability related to wind generation.[8] [A] *Hourly demand and generation for March 14th 2014,* [B] *Hourly Percentage Generation by Resource for March 14th 2014,* [C] *Monthly (Hourly) Average Generation Values (2011-2014), and* [D] *Aggregate Daily Generation (2011-2014).*[8]

2.b.ii Geothermal Energy

With 5,500 MW of geothermal reserves, Nicaragua has the largest geothermal potential of any Central American country.[20] Within the chain of 18 volcanic centers found in Nicaragua's west coast, and as part of the Central America Volcanic Arc (CAVA), there are 9 regions with a cumulative total of 4,195MW Possible, 675MW Probable, and 303MW Proven reserves.[20] Currently, only about

160MW have been fully developed. Although geothermal contributes about 16% of total annual power production, its oldest geothermal production well (Momotombo) were initially overexploited and currently work at 40% of rated capacity, but its most recent production-well (San Jacinto Tizate), has been producing at almost full rated capacity (72MW).[34] Full development of Nicaragua's geothermal potential is complicated as most is situated within protected areas, however, there are ways in which these projects could be developed sustainably using joint use lands, such as recent efforts at Kenya's principal geothermal resource, the Olkaria Field, located in Hell's Gate National Park.[35] Additionally, environmental considerations must be ensured, particularly in light of Nicaragua's water-access stress levels, as although geothermal sources are considered renewable, they can have significant environmental and socio-economic impacts including: surface disturbances, physical effects due to fluid withdrawal, thermal effects and chemical emissions (gas and liquid discharges), and displacement of local communities.[36] The country has planned to develop eight more geothermal projects (17 production wells), with an average installed capacity of 30MW between 2018 and 2028 for a total of 527MW).[7] In 2012 Nicaragua also finished a five-year geothermal capacity building project with the Icelandic International Development Agency (IIDA) (Geothermal Building Capacity). Geothermal production is used as a baseload throughout the year, and on average, it is not used as flexible generator (please see appendix for details).

2.b.iii Hydropower

Hydropower in Nicaragua has already begun feeling the immediate impacts of extreme climatic events. In 1998 Hurricane Mitch, severely damaged four hydroelectric stations, the worst being Santa Barbara (largest hydropower station at the time), rendering it out of service by destroying its fuse plug, damaging its spillway, water conveyance works, access roads and engine houses.[37] Dams, spillways, water conveyance channels, and silting also damaged Planta Centroamerica (still operational), as well as several micro-hydropower centrals in the region.[37] More recently, it has begun experiencing the effects of anthropogenic climate change by seeing its first hydropower station ('Las Canoas') go dry (and left unserviceable) in 2010, due to a combination of a deep and prolonged drought and water use conflict between rice farmers, residential areas, and power production.[38] Regional climate change models of Central America suggest that hydropower will be increasingly affected by: 1) reduction of rainy days (more dry years), 2) an increase in the frequency and intensity of extreme wet events, and 3) increased silting.[31,39] If one takes into account the effect that increased temperatures could have on hydropower reservoirs (increased evapotranspiration), and compound the effects of deforestation, the effects could be devastating.[40] In the Xingu River basin (Brazilian Amazon), under a business-as-usual projections of forest loss by 2050 (40%), simulated power generation declined by 25% of maximum power output.[40] Without detailed studies of how the combined impacts of natural climatic variability, anthropogenic climate change and deforestation could have on hydropower, it is difficult to assess the sustainability of the resource's future in the country.

Currently the country operates three hydropower plants (112MW installed capacity), generating about 11% of total power production.[8] On average, hydropower is used as a baseload, but contrary to geothermal production it is also dispatched to cover for wind intermittency, as well as behaving as a peaking plant at times of highest energy consumption. Hydropower is seasonal in nature, with production being the highest during the rainy season (May – November). Although Nicaragua currently is planning to build 16 more power plants between 2013 and 2030 (924MW), including three mega projects (Tumarin 253MW, Boboke 120MW, Copalar Bajo 150MW), it is extremely important that each project's sustainability is assessed by taking into account socio-economic impacts, as well as natural hydrological variability, climatic change, and anthropogenic stresses.

2.b.iv Biomass

Nicaragua, like the rest of Central America has more than two decades of experience in using agricultural residues for electricity. Since 1998, Nicaragua has used *bagasse* (sugarcane stalks) to generate electricity (49MW installed capacity), and in 2002, the country completed the construction of another 77MW biomass generation unit, and today agricultural residues compose 6% of the country's total generation.[8] More recently, Nicaragua and other Central American countries have begun considering the use of residues from pineapple, banana production, animal waste, and wastewater for energy generation.[33]

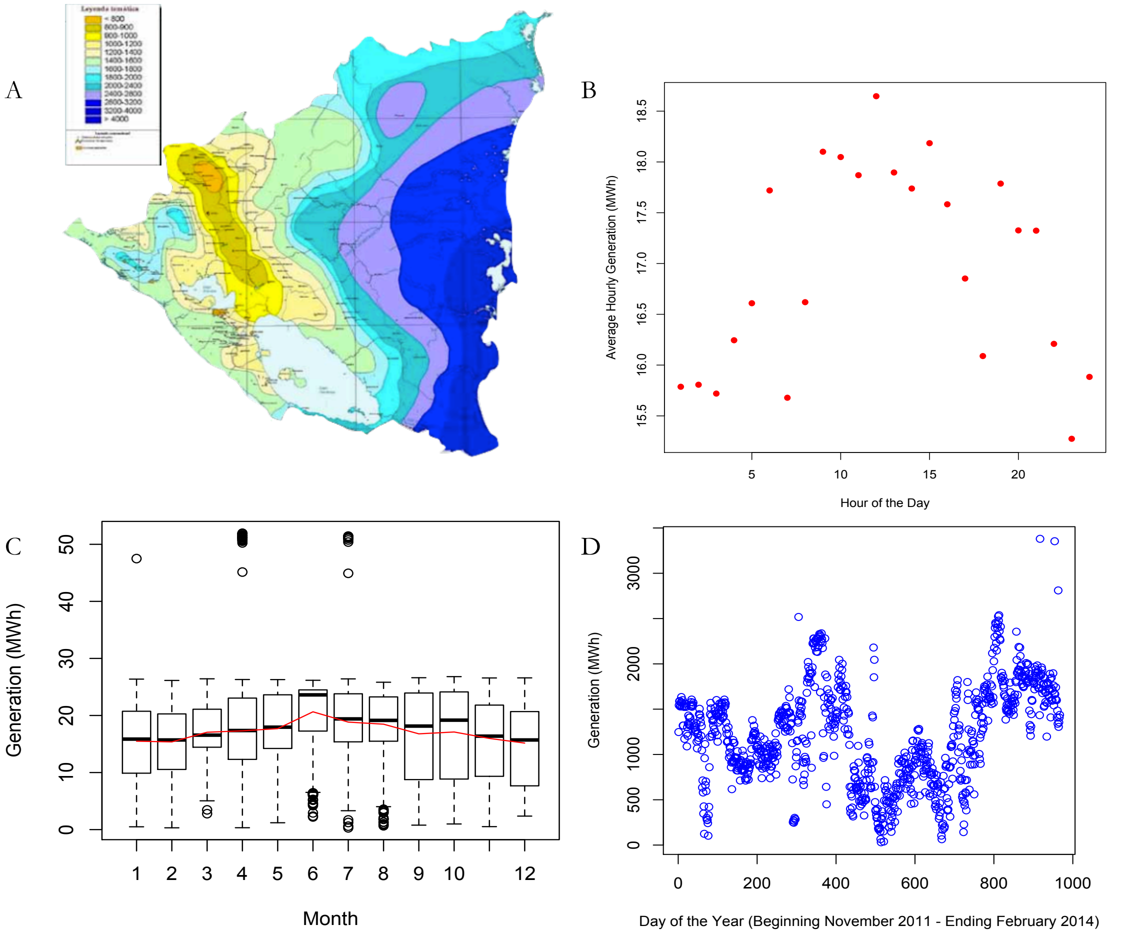


Figure 6. Spatio-temporal Variability of Hydropower Generation (MWh) in Nicaragua. [A] *Map of Mean Annual Precipitation in Nicaragua (mm/year),* [B] *Average hourly wind generation (all plants, MWh),* [C] *Boxplot of monthly (hourly) hydro generation (inter-annual variability, MWh), and* [D] *Aggregate Daily Generation and Seasonal variability (July 2011 – February 2014).*

Although converting agricultural waste into energy is without doubt a great success for Nicaragua and the rest of Central America – workers health has been jeopardized throughout the region. Without being able to pin down the exact cause of the disease, chronic kidney disease of unknown etiology (CKDu) has been spreading as an epidemic through the lowlands of Central America's Pacific coast, being first reported in 2002.[41] The disease is most prevalent amongst cane cutters, and although it has been hard to pinpoint the exact cause (dehydration and heat stress, pathogens, agrochemicals, heavy metals and or biochemical disorders), most experts signal worker conditions (chronic dehydration and heat stress) to an increased susceptibility to the nephrotoxic effects of pesticides.[41] As grassroots movements have begun protesting worker's rights, and researchers from around the world have begun to investigate what has been called 'Mesoamerica's mystery killer', certainly, large-scale biomass' future in electricity generation will be unavoidably tied to worker's quality of life.[41] Nicaragua's bagasse plants are located in pacific coast, serving as non-peaking baseload generators.[8] Sugarcane has a six-month cycle from November to May, and thus bagasse availability is highest at the time when rainfall (and hydropower production) is low and electricity demand is high.[26]

2.c Intermittent Renewable Energy

2.ci Wind

Nicaragua installed its first wind energy plant in 2009 (40MW), and 5 years later, its wind-installed capacity has more than quadrupled (186.6 MW). A scoping study by the National Renewable Energy Laboratory (NREL) in 2005 denoted class 6 winds superb (600 – 800 W/m^2; 8. – 8.8 m/s at 50 m) and prevalent across the western shores of Lake Nicaragua, as well as the southwestern part of the country in San Juan del Sur (figure 7).[42] Thus far, five large-scale wind farms (38Mw on average) have been built on the shores of Lake Managua in the southwestern part of the country, and 260 MW more of wind are planned to be built between 2014 and 2030 (Data MEM). Despite this great progress, however, large, easily accessible western areas of the country with great wind potential have yet to be included in the planning process. On an annual average, Nicaragua currently generates approximately 13% of its total generation with wind energy.[8] At peak production, on the other hand, wind energy can produce as much as 45% of the country's total production on an hourly basis.[8] Spatio-temporal correlation between the five plants located in the shores of lake Managua is high (0.53), and on average, they present both similar patterns in hourly and monthly variability (please see appendix for details). On a daily average, wind generation drops at 10 am and begins rising again at 3.00 pm. On a monthly basis, wind generation drops in March and rises in October, with the periods of greatest hourly wind generation and variability occurring during the rainy season (May – November).

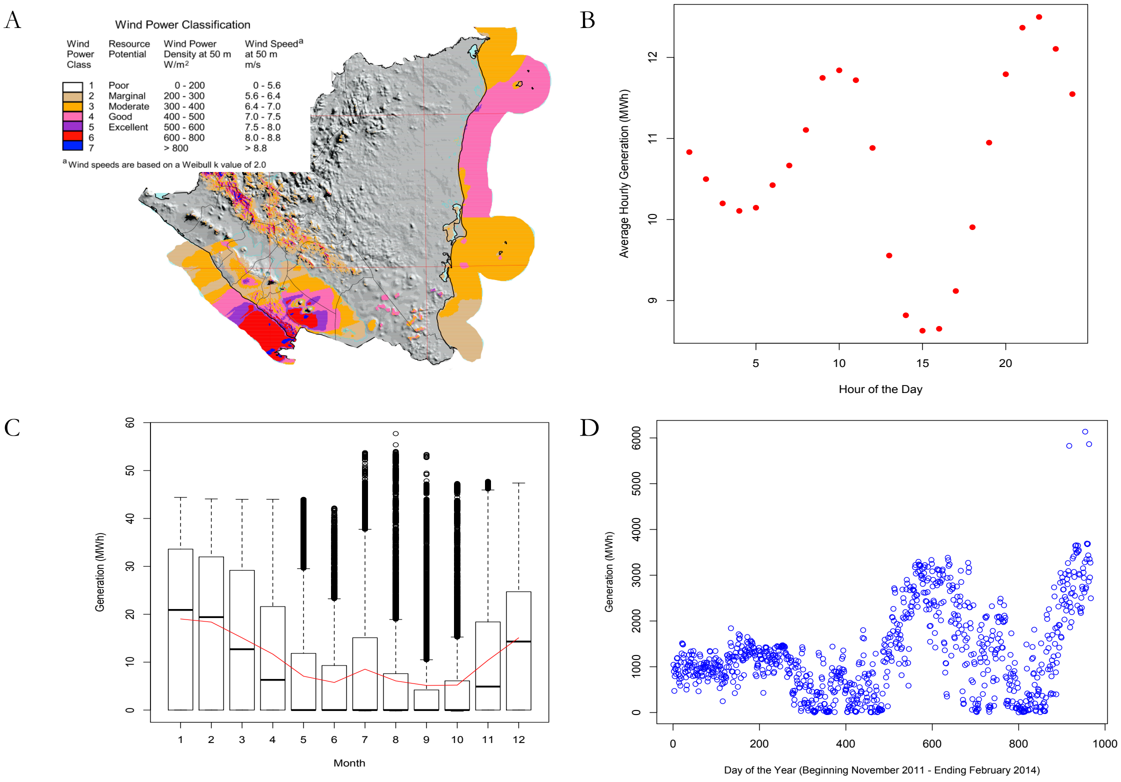


Figure 7. Spatio-temporal variability of wind generation (MWh) in Nicaragua. [A] *Map of Wind Potential in Nicaragua,* [B] *Average hourly wind generation (all plants, MWh),* [C] *Boxplot of monthly wind generation (inter-annual variability, MWh), and* [D] *Seasonal variability (July 2011 – February 2014). Note: Zeroes are used to compute the average.*

2.cii Rooftop PV and Central Generation

Despite its large potential, solar generation in Central America and Nicaragua has gone largely underutilized. Although Costa Rica and Nicaragua have both installed 1MW utility scale central PV projects (enough to power over 1,000 households) in the last two years, the region has no concrete plans for further development.[33] The fact that both 1MW project costs, averaging $US12 million/MW ($US12/W), were three times higher than central PV costs in the United States ($4.05/W),[43] could have influenced the country's and region's perspective on solar generation. This should not signal, however, a final hiatus for industry development, as international experience from other emerging economies has also shown that renewable energy technologies in new markets tend to be significantly above the global average at earlier stages of development.[44] Commercial scale and rooftop-PV installations on the other hand, have been adopted in a wide range of small, distributed applications throughout the region.[33] Thousands of low-income rural households have been electrified via off-grid and grid-tied PV installations,[33] and as electricity prices continue to rise, peri-urban areas, urban households and small businesses could find themselves increasingly motivated by a desire to reduce both costs and increase their own energy reliability.[33] Average solar global irradiation in Nicaragua is 5.21kWh/m^2-day with the Pacific and Central part of the country receiving the most sunlight throughout the year.[45] Global irradiation averages range as high as 5.7 kWh/m^2-day in Matagalpa, to as low as 4.6 kWh/m^2-day in Madriz. In terms of seasonal variability, February-May are both the hottest and sunniest months of the year, while the rainy season (June – November) has the lowest irradiation levels.[45] The next section uses national hourly irradiation data to model the integration of grid tied central and rooftop PV plants into Nicaragua's electric grid (please see appendix for details).

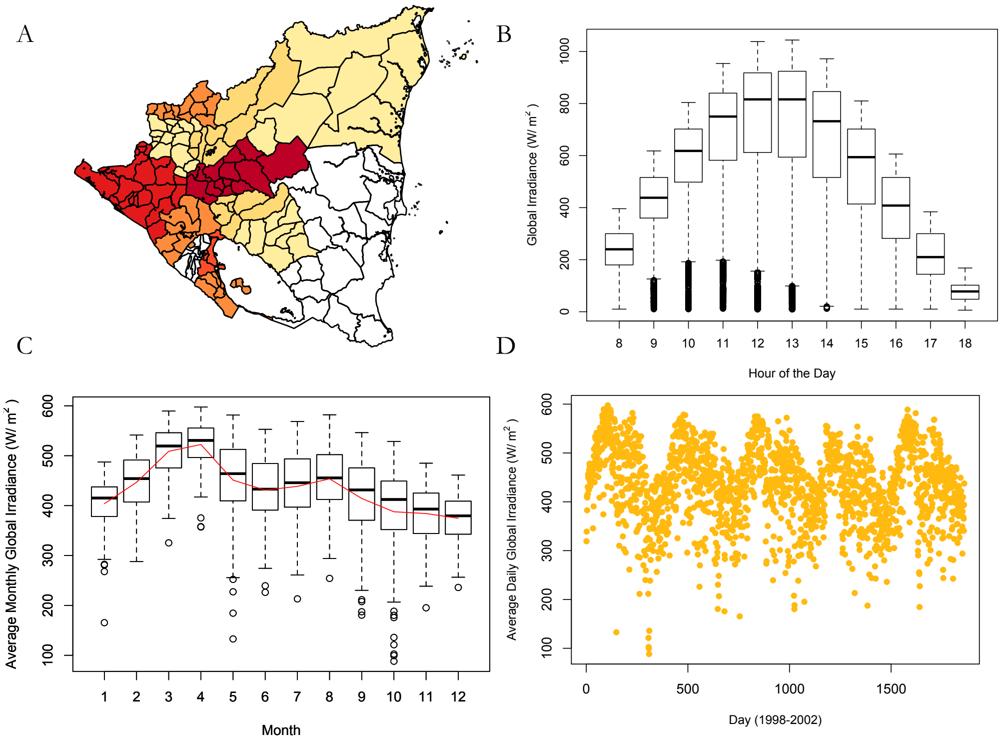


Figure 8. Spatio-temporal variability of solar irradiation (W/m^2) in Nicaragua. [A] *Map of Solar Irradiation*, [B] *Average hourly solar irradiation (W/m^2)*, [C] *Boxplot of monthly (hourly) irradiation, and* [D] *Seasonal variability (July 2011 – February 2014).*

3. SWITCH – Nicaragua: Modeling a Present and Future Low-Carbon Grid

Here we use SWITCH (a loose acronym for Solar, Wind, Hydro and Conventional generation and Transmission Investment) as a planning tool for Nicaragua's electric power system, to model and optimize the capacity expansion of renewable and conventional generation technologies, storage technologies, and the transmission system while explicitly accounting for the hourly variability of intermittent renewable energy.[9,10,11] SWITCH is a mixed-integer linear program (LP) whose objective function is to minimize the cost (generation, storage, and transmission) of delivering power, every hour, to every load area in a country (or region), subject to operational and policy constraints. [9,10,11] Although there are several SWITCH international models under development (Chile, China, and India), SWITCH has been used most extensively to model high renewables penetration scenarios within the Western Electricity Coordinating Council (WECC),[9,10,11] exploring a variety of scenarios including SunShot Central PV prices, high/low natural gas prices, and high/low concentrated solar prices.[9,10,11] We use SWITCH to model a base cost scenario to explore high renewable energy penetration strategies in Nicaragua.

3.a Data

Investment periods, months, days, and hours are used in this study's data temporal structure to simulate Nicaragua's electric system power dynamics from 2014-2030. There are four four-year-long investment periods: 2014-2018, 2019-2023, and 2024-2028, each containing historical data from 12 months, two days per month, and 12 hours per day. Peak and median load days are weighted differently (peak load days are given a weight of one day per month, and median days, are given a weight of the number of days in a given month minus one) to both represent load and weather variability, as well as to ensure that the system is dispatching under typical load conditions, and incorporating capacity planning for periods of high grid stress.[9,10,11] Hourly national load data (July 2011 – March 2014) were extracted from Nicaragua's National Dispatch Center website (CNDC), and disaggregated into 16 different load areas throughout the country depending on each load area's relative consumption. This hourly load data is scaled to project future demand (2014-2030) using Nicaragua's Ministry of Energy and Mines (MEM) demand projections.[7,8]

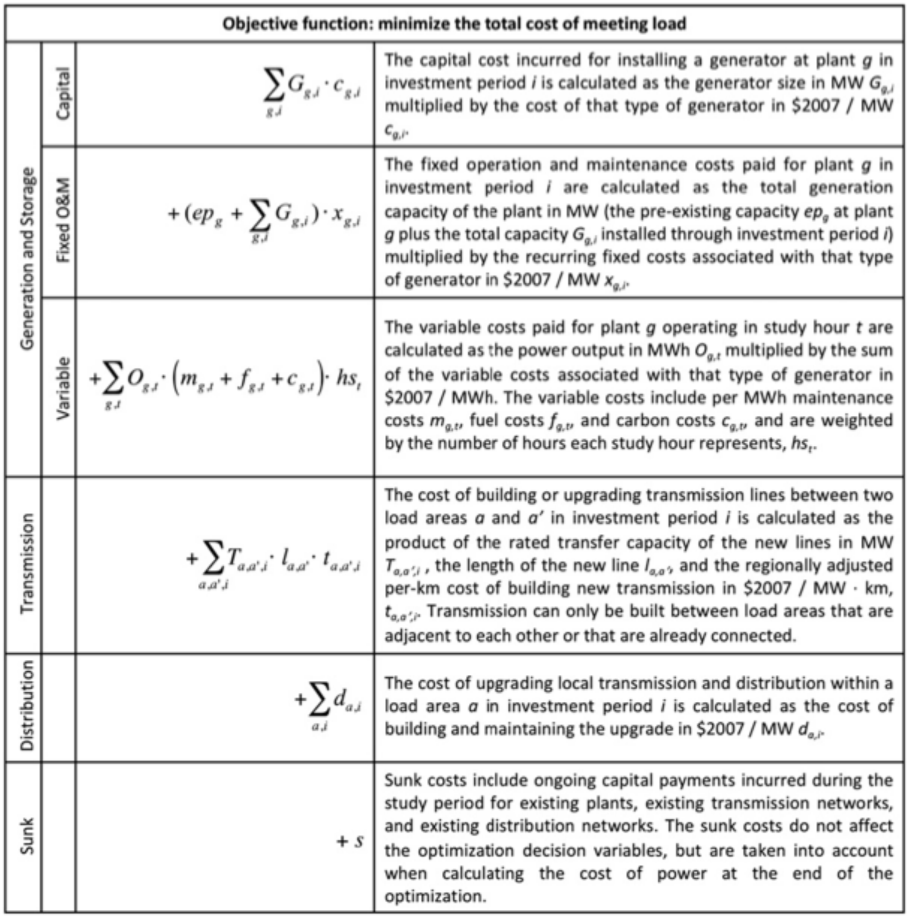
For existing generation plants, we use historical hourly generation profiles (July 2011 – March 2014) extracted from CNDC's website for 24 bunker fuel oil thermal plants, two geothermal generators, two biomass generators, three hydropower plants and 6 wind generation plants. Existing and future generator specifications and characteristics were obtained from MEM and INE, and we use historical resource specific generation profiles to simulate hourly outputs for new thermal and non-intermittent renewable generation projects (geothermal, biomass, and hydroelectric) (2014-2030). For our optimization problem constraints (detailed below), we de-rate the nameplate capacity of grid assets by their forced outage rates (for every power output hour), and further de-rate them by their scheduled outage rates if they are baseload generators.[9,10,11] We use simulated historical hourly generation profiles for a portfolio of 5 new (planned) 50MW wind farms on the western shores of lake Nicaragua, and we allow SWITCH to expand generation through the lake's shores as well as the Pacific coast of San Juan del Sur (assuming 5MW/km^2),[42] taking advantage of the region's excellent wind conditions, while respecting protected areas (such as the wildlife refuge Rio Escalante Chacocente). Hourly solar rooftop and central-PV generation output is simulated using hourly solar irradiation profiles from around the country,[45] and we build enough central PV and rooftop potential to help meet 5% of Managua's peak daily demand with solar power (see appendix for details). Current and future hourly load and generation profiles are time-synchronized, allowing SWITCH to capture the temporal relationship between load and renewable power output levels.[9,10,11]

For each generator (thermal bunker fuel oil, non-intermittent renewables, and intermittent renewables) fixed O&M costs (those related to expenditures for items used over an extended period of time, and independent of the amount of the electricity generated by the plant),[46] non-fuel variable O&M (those expenditures consumed within a short period of time, and dependent directly on electricity generation), and overnight construction capital costs (describing the cost of completely building a power plant 'overnight', without taking into account financing costs or interest escalation) are collected.[47] Costs for building and/or upgrading transmission lines between two load areas, within a load area, and sunk costs (ongoing capital payments incurred during a study period for existing plants, and existing transmission and distribution networks) are also included in the analysis.[9,10,11] As building more plants of the same technology involves learning, and economies of scale, we use an exponential decay function using a capital cost declination rate so that new technologies become cheaper in future study periods.[9,10,11] We assume that rooftop and Central PV experience the fastest overnight cost declination rates (-4.85%/year and -3.73%/year respectively).[9,10,11] Construction costs are tallied yearly, discounted to present value when the project comes online, and then amortized over the operational lifetime of the project.[9,10,11] Connection costs for new generators are incurred one year before operation begins, and O&M costs are experienced throughout the project's lifetime.[9,10,11]All costs are discounted to present day value using a 7% real discount rate, and they are expressed in real $US2014 dollars. Bunker fuel oil and biomass prices and projections are obtained from Nicaragua's Ministry of Energy and Mines. For our analysis Nicaragua is divided into sixteen load areas, representing areas of the grid within which there is significant existing local transmission and distribution, but between which there may be limited long-range, high-voltage existing transmission.[9,10,11] Powerflow between the SIEPAC Central American interconnection line is not considered.

3.b Model Specification and Baseline Scenario

SWITCH is a mixed-integer linear program whose objective function is to minimize the cost of meeting projected electricity demand with generation, storage, and transmission between 2014 and 2030. Although SWITCH does not model the electric properties of the transmission network in detail, it does take into account the maximum transfer capacity of transmission lines, modeling them as a generic transportation network with maximum transfer capabilities equal to the sum of the thermal limits of individual transmission lines between each pair of load areas.[9,10,11] Investment and dispatch variables are the two main sets of decision variables in the linear program. As such, and for each investment period, capacity investment variables determine the amount of new capacity and transmission to install as well as the amount of MWs of older plants to retire.[9,10,11] Baseload (hourly power produced: generator capacity de-rated for forced and scheduled outages) and intermittent (hourly power produced: generator capacity *x* hourly capacity factor) power output is determined through capacity investment variables. In SWITCH – Nicaragua dispatch variables (all subject to capacity constraints set by investment decision variables) control the amount of hydroelectric power that can be generated, and the amount of power to transfer along each transmission corridor.[9,10,11] We optimize hourly dispatch of generation and transmission simultaneously with investment decisions.[9,10,11]

Our operational and policy constraints include those that ensure that projected demand is met, those that maintain the reserve margin, and those that enforce a renewable portfolio standard (RPS). Demand constraints ensure that the available power infrastructure is dispatched to meet load in every hour in every load area in Nicaragua while providing the least expensive power based on expected generation and transmission availability.[9,10,11] SWITCH also constrains the system so that it maintains a 'safe' planning reserve at all times, ensuring that the system has sufficient capacity available to provide at least 15% extra power above load for every hour, in every load area of the country. The optimization problem determines the reserve margin schedule concurrently with the load-serving dispatch schedule. Finally, an RPS constraint ensures that the system uses a minimum amount of renewable energy resources in each investment period for the entire country.[9,10,11]



Objective function: minimize the total cost of meeting load			
Generation and Storage	Capital	$\sum_{g,i} G_{g,i} \cdot c_{g,i}$	The capital cost incurred for installing a generator at plant *g* in investment period *i* is calculated as the generator size in MW $G_{g,i}$ multiplied by the cost of that type of generator in $2007 / MW $c_{g,i}$.
	Fixed O&M	$+ (ep_g + \sum_{g,i} G_{g,i}) \cdot x_{g,i}$	The fixed operation and maintenance costs paid for plant *g* in investment period *i* are calculated as the total generation capacity of the plant in MW (the pre-existing capacity ep_g at plant *g* plus the total capacity $G_{g,i}$ installed through investment period *i*) multiplied by the recurring fixed costs associated with that type of generator in $2007 / MW $x_{g,i}$.
	Variable	$+ \sum_{g,t} O_{g,t} \cdot \left(m_{g,t} + f_{g,t} + c_{g,t}\right) \cdot hs_t$	The variable costs paid for plant *g* operating in study hour *t* are calculated as the power output in MWh $O_{g,t}$ multiplied by the sum of the variable costs associated with that type of generator in $2007 / MWh. The variable costs include per MWh maintenance costs $m_{g,t}$, fuel costs $f_{g,t}$, and carbon costs $c_{g,t}$, and are weighted by the number of hours each study hour represents, hs_t.
Transmission		$+ \sum_{a,a',i} T_{a,a',i} \cdot l_{a,a'} \cdot t_{a,a',i}$	The cost of building or upgrading transmission lines between two load areas *a* and *a'* in investment period *i* is calculated as the product of the rated transfer capacity of the new lines in MW $T_{a,a',i}$, the length of the new line $l_{a,a'}$, and the regionally adjusted per-km cost of building new transmission in $2007 / MW · km, $t_{a,a',i}$. Transmission can only be built between load areas that are adjacent to each other or that are already connected.
Distribution		$+ \sum_{a,i} d_{a,i}$	The cost of upgrading local transmission and distribution within a load area *a* in investment period *i* is calculated as the cost of building and maintaining the upgrade in $2007 / MW $d_{a,i}$.
Sunk		$+ s$	Sunk costs include ongoing capital payments incurred during the study period for existing plants, existing transmission networks, and existing distribution networks. The sunk costs do not affect the optimization decision variables, but are taken into account when calculating the cost of power at the end of the optimization.

Table 1. Objective function of SWITCH. *Credit: SWITCH California*.[9,10,11] For full details on the SWITCH optimization framework, objective function and constraints please visit the extensive model documentation developed by RAEL.

Our baseline scenario investigates a base cost scenario, where we allow SWITCH to plan the system from 2014-2030 allowing full and immediate availability of all potential technologies and projects (biomass, wind, rooftop and central PV, geothermal, run of river and reservoir hydropower, bunker fuel oil plants, and battery storage). Initially, we have constrained the SIEPAC interconnection line that will soon connect all of Central America, unconstrained capacity in transmission lines (and thus no new transmission will be built) and only allow reservoir hydro the ability to provide spinning and quickstart capacity reserves, while bunker fuel oil can only provide quickstart (non-spinning) capacity reserves. We do not provide a national renewable portfolio standard, as we investigate the base scenario, where the system is deployed most cost-effectively without policy constraints.

3.c Results and Discussion

Our base cost scenario (with no RPS policy implemented) gives us a least-cost system that obtains 40% of its power from distillate fuel oil in the first time period (2014-2017), and only 20%, 6%, and 4% in the subsequent time periods. Our first time period is similar to the currently existing one, which gives us confidence in our results (using data from 2011-2013 we had found Nicaragua's current energy mix to be composed of 53% bunker fuel oil, 16% geothermal generation, 13% wind, 11% hydropower, and 6% biomass production). Although the least-cost system still builds additional distillate fuel oil generators, these are primarily used as spinning and quickstart capacity reserves in all time periods. In the first time period, distillate fuel oil plants provide 80% of the total operating reserves (12% spinning reserves, 100% quickstart reserves), 70% in the second period (27% spinning reserves, 99% quickstart reserves), 50% in the third period (5% spinning reserves, 81% quickstart reserves), and 60% in the fourth investment period (5% spinning reserves, 98% quickstart reserves). Reservoir hydropower plays an important role with regards to system flexibility as it provides, on average, over half of the system's spinning reserve requirements. On average, the role that bunker fuel oil plants built prior to our first time period play throughout our study period is that of generation (43%) and that of providing quickstart reserve capacity (53%). This means that on an hourly average, any given bunker fuel oil plant is delivering power at 43%, providing quickstart reserve capacities at 53%, and using 5% for reserve capacity. New bunker fuel oil plants use on average 95% of their generation potential for providing quickstart capacity reserves, and only 5% for actually generating power.

On the other hand, and although hydropower also provides grid flexibility (they provide ≥ 50% of spinning reserves), run of river (≤ 30MW) plants built before our first time period, use 80% of their operational availability for generation, and 20% for spinning reserve requirements. Similarly, new hydropower plants (run of river ≤ 30MW, run of river ≥ 30MW, and reservoir hydropower ≥ 30 MW) use 98% of their operational availability for generation, and only 2% for spinning reserve. Geothermal, biomass, and wind operations are purely generational (100%). Although this base-cost scenario captures some important dynamics of Nicaragua's power sector, our initial constraints drive the model and the results. For example, we do not allow neither geothermal nor biomass projects to provide ancillary services, although both resources are abundant in the country. Important further extensions and scenarios to the model will allow for the deployment of storage, allowing geothermal and biomass to provide ancillary services (spinning and non-spinning reserves), a solar mandate, and a moratorium on oil developments.

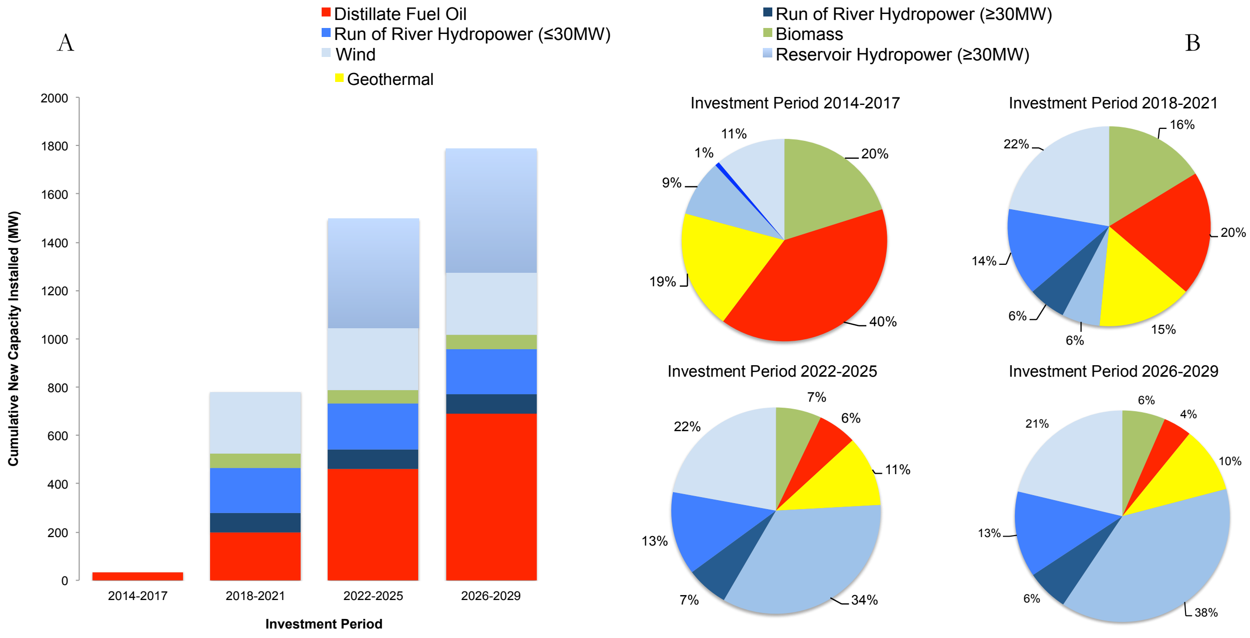


Figure 9. Base cost scenario cumulative new capacity additions [A], and percentage of generation mix by resource and investment period [B].

Capital and fixed costs for existing generating units decrease over time as both existing biomass plants are retired (the first 55MWs are retired in the first period, and the second 79MW are retired at the end of the second period), in addition to 134MW of distillate fuel oil and 35MW of geothermal of installed capacity that go offline by the beginning of the third period. As new projects come online, the third (2022-2025) and fourth (2026-2029) time periods increase fixed and capital costs by 140% (relative to the first investment period), with reservoir hydropower (≥ 30 MW) accruing most of the costs. Although distillate fuel oil plants represent the largest cumulative installed capacity additions, they represent some of the cheapest system investments (~$US overnight cost

500,000/MW) together with run of river hydropower (≤ 30 MW; ~$US overnight cost 2 million/MW) and biomass generation (~$US overnight cost 2.4 million/MW). With respect to operational costs, however, distillate fuel oil plants are the only plants that incur fuel expenditures and these entail 98% of their variable costs (2% non-fuel variable costs). During the first investment period (three years) approximately $US 2 billion dollars are spent on bunker fuel oil costs, $US600 million dollars less are spent in the second time period, and $US800 million less in the third period. The final investment period (2026-2029) spends approximately $US350 million on fuel oil. Per investment period, on average, distillate fuel oil expenditures amount to approximately $US1 billion dollars ($US 300 million/year). To contextualize the magnitude of this costs it is worth noting that Nicaragua's GDP ($US 2012) was ~$US 11 billion in 2013. The levelized cost of electricity from the first to the fourth period is $US282.23/MWh, $US294.54/MWh, $US244.06/MWh and $US211.28/MWh respectively.

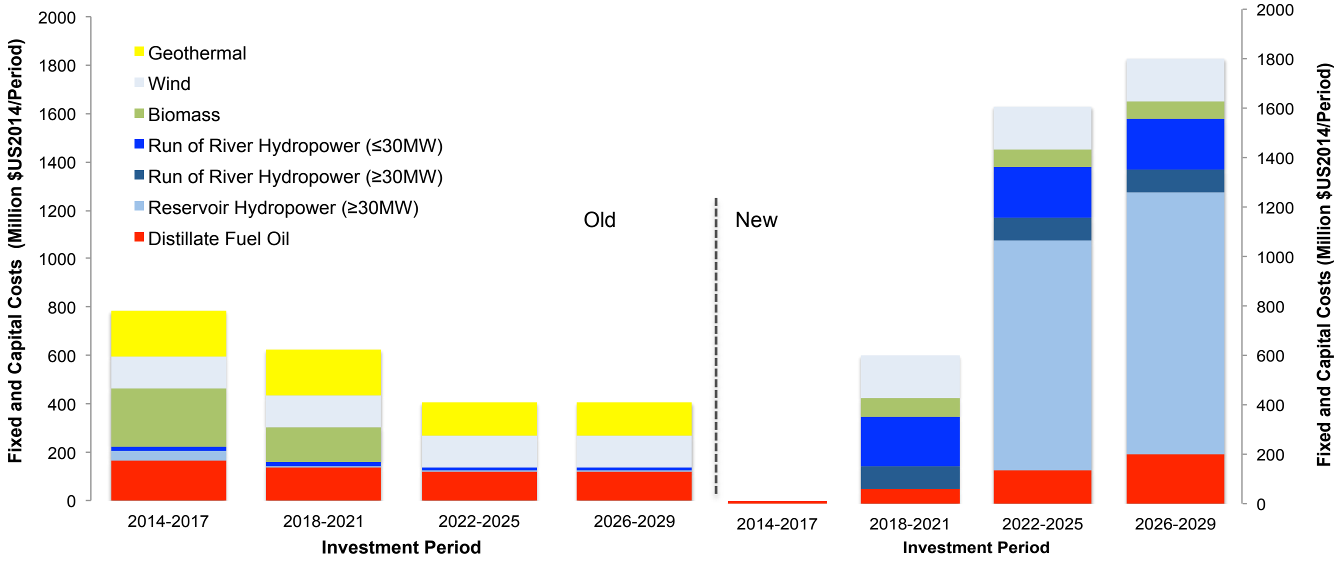


Figure 10. Period average fixed and capital costs for old (left) and new (right) projects.

There are several electricity system dynamics that are not taken into account in our base cost scenario. It is likely that allowing supply and demand interactions through the SIEPAC line would drive system costs down substantially as Nicaragua's grid imbalances could be met through imports and exports. Although such interactions through the SIEPAC line already exist, they merely account for 1% of the total amount of power generated in Nicaragua. Geothermal and biomass generation are modeled here as non-flexible resources and thus SWITCH finds their use sub-optimal, as they compete with hydropower to provide baseload power without providing additional ancillary services to the grid. Thus, no new geothermal power is built, and only two out of four potential biomass projects are developed. If one took into account the risk related to hydro-climatological variability and the impact that deforestation will surely have on hydropower power production, benefits from Nicaragua's rich geothermal and biomass resource would likely increase. Another limitation from our study is that transmission is not constrained to its thermal limits, and thus, no new transmission is built along existing (and non-existing) load area transmission corridors. Future SWITCH – Nicaragua implementations will include thermal line limits (and allow for transmission development), will model flexible geothermal and biomass generation, and will allow imports and exports across the SIEPAC line. We expect this to have significant impacts (in both directions) on both technology deployments and system costs.

Although our base cost scenario does model important dynamics of Nicaragua's electric power sector, we do not include any policy constraints. Work is currently underway to incorporate a national renewable portfolio standard, placing a moratorium on distillate fuel oil and large hydro development, and implementing a solar mandate, as preliminary findings show great potential for rooftop and PV development (please see appendix). We expect that these constraints would allow SWITCH to incorporate the dynamics of more geothermal and biomass deployment, as well as storage (pumped hydro and grid tied battery storage). Future SWITCH-Nicaragua runs will also reduce the 15% reserve requirement constraint, as we believe that this substantially increases spinning and quicktart capital expenditures in a country that has historically used load shedding as demand response strategy. Finally, and not addressed in this paper, is the need to better understand the complexity and dynamics of providing reliable electricity services to approximately 20% of the population that remains un-electrified. Future work will also evaluate compare the cost-effectiveness, and other benefits of providing reliable electricity services via microgrid-decentralized services as opposed to expanding the existing infrastructure.

4. Conclusion: Renewable Energy for People and Planet in Nicaragua

Nicaragua currently finds itself at the cusp of achieving energy independence, and transitioning to a low-carbon electricity system. Furthermore, Nicaragua has achieved this much sooner, and at an earlier stage of development than many other countries around the world (including regions like California, and some parts of Europe). At it's current level of income per capita ($US 5000/capita, 2005 dollars) and energy consumption per capita (1,300 kWh/capita), it's electricity system has a much larger share of non-hydro renewable energy than any European country, when these countries were at the same level of income and electricity consumption per capita.[4] In Latin America, countries such as Costa Rica, Chile, Mexico and Uruguay had only reached non-hydro renewable energy penetration levels of 18%, 7%, 4% and 0.65% respectively, when they were at the same level of Nicaragua's current state of development. Although this progress is certainly laudable, this also means that Nicaragua will experience a panoply of renewable energy related technical and social challenges at an earlier stage of development than other countries have.

Technical challenges present Nicaragua an opportunity to 'leap frog' from an electricity system (distribution, transmission and generation) that has traditionally lacked investment, to a 'smart'- and more reliable electricity system. As such, if we take a low-carbon future to be a foregone conclusion in Nicaragua, stronger and more reliable integration is the next frontier. While SWITCH-Nicaragua can help us explore utility grid deployment scenarios for different combinations of renewable energy technologies, thinking about how these technologies will be integrated into the existing infrastructure (residential, buildings, industry and transport) presents a great opportunity for other types of more applied ('on the ground') research, technology deployment, and innovative business models. Grid integration solutions are not only technical, but they will also require planning, and market-regulatory changes including*: 1)* power markets that support greater flexibility, *2*) greater coordination of grid operators and balancing areas, and *3)* using power dispatch models that can incorporate day-ahead weather forecasts for wind speeds and solar insolation.[1] Specifically for Nicaragua, controlled curtailment (already in place), demand response, strengthened transmission capacity and interconnection (already in place albeit in small amounts), expanding resource diversity within geographic grid and balancing areas, and energy storage could provide greater system flexibility. Although DR is a broad phrase that covers a wide range of actions, Nicaragua's residential load curve and a growing manufacturing industry could allow for earlier adoption of DR strategies into a variety of consumption patterns and engineering processes. DR in Nicaragua could help avoid future installed capacity costs, contribute to peak shaving, and reduce the need for contingency and regulatory reserves, which in our results significantly increases system costs. DR strategies, however, are yet to be explored in Nicaragua. Storage through hydropower and/or grid-tied battery storage is another possibility that has yet to be explored in Nicaragua, and its future, could be greatly enhanced and proved most cost-effective if used in tandem with the previously mentioned strategies.

Social challenges to renewable energy have recently sprung throughout all corners of the world, and if renewable energy is to have a bright future in Nicaragua, it must learn from other countries history and past mistakes. Take Denmark for example, that saw the active support and positive involvement of the population as a determining factor in wind technology successfully taking off and coming of age in the country.[48] Beginning in the late 1970's, wind energy policy allowed all farmers rights to install one turbine on their land, local residents could form wind cooperatives and jointly own wind parks (limiting the shares that any individual could own) and utilities could build large wind farms in agreement with the government.[48] This ownership model, one that allowed individuals and municipalities to gather and profit from renewable resources, was critical for wind's success in Denmark and particularly important for the high public acceptance that wind enjoyed during that time.[48] After economic liberalization began in 1998, limits on shares owned by a particular individual were abolished, changing the ownership model dramatically and beginning a take-over bid competition, where anyone could own as many windmills as they could, anywhere in the country.[48] Financial investors also begun buying windmills from cooperatives, and as a result, today, attitude towards wind has completely changed turning what was a cooperative model into bitter conflicts over land and money, leading to long delays and project cancellations.[48] Nicaragua's progress in large-scale wind and renewables development business model does not include community development, and although its growth has been rapid, failure to develop wind and community projects jointly could halt the country's low-carbon energy transition on its feet.

More recently and for similar social-tensions, large-scale wind developments in Mexico and China have begun to face fierce resistance by community led movements. In the Isthmus de Tehuantepec (Mexico), estimates by NREL have suggested that about 3.5GW of wind generation capacity could be installed in areas with good and excellent conditions, and 4.4GW if one considers areas of moderate potential.[49] With this potential, large projects have been developed and more are being planned without including communities in the area. Entrepreneurs, companies and Mexican government officials have begun a process of territorial division where communities play no role.[50] In an area characterized by farming, poverty, and strong winds, 'wind deals' involved giving land owners 1.5% of the gross income resulting from energy production, in exchange for the exclusive right to use the land for wind generation.[50] This amount does not depend on the number of landowners, with a share going to owners where the turbines are erected, another to owners of land affected by roads and/or transmission lines, and another to others whose property is not directly affected by wind but whose actions (planting trees, farming, building houses) could affect wind generation.[50] Some landowners have signed contracts as low as $US150/hectare-year. This way of doing business in a region with rich indigenous cultural diversity (Zapotecas, Huaves, Mixes, Chontales and Zoques) has led to companies being sued, deaths, and threats related to bitter land conflicts, in addition to long delays in wind project development.[50] In China (the largest wind developer in the world), villagers from Dongzhou village put the number of dead as high as twenty, in addition to farmers being jailed from three to seven years after villagers protested against the lack of compensation for land lost to a wind power plant in Guangdong province.[51]

Just like there have been social-challenges to renewable energy adoption, there are also success stories, and yet, Nicaragua will have to pave and find its own way of making renewable energy work for people and planet – solutions and 'best practices' are not clear cut. Examples include the success for people and wind in the municipality of Sydthy (Denmark),[52] the development, promotion and dissemination of household biogas in rural India and Mexico (Sistema Biobolsa),[53,54] and in Nicaragua, the very own work of micro-hydro development initiated by Ben Linder and continued to this day by Rebecca Leaf, as well as blueEnergy's small scale wind developments in the Atlantic Coast of Nicaragua.[55] With 20% of its population being still without access to reliable electricity services, Nicaragua has a great opportunity to make off-grid small-scale renewable energy (small-scale biomass resources and biogas in the Atlantic Coast, for example) a reality.

While this research has shown that even without a national RPS and other strong policy mechanisms renewable energy (intermittent and non-intermittent) can be a cost-effective long-term strategy for Nicaragua's electricity system, there are important considerations that we have left out of this study. First, the results described here are only from our base-cost scenario, and thus, provide limited guidance of the different ways and investment pathways through which a low-carbon system in Nicaragua could be achieved. Like mentioned earlier, accurately modeling of geothermal and biomass flexible generators, including pumped and grid-tied battery storage, and enabling interconnecting ties would likely reduce system costs and provide greater system flexibility. Modeling the impact of policy mechanisms such as a moratorium on oil and large hydro development, and a solar mandate could also significantly affect the results. Also, SWITCH – Nicaragua cannot fully predict the impact of DR strategies in the country, as there is little research that has evaluated the implementation and effectiveness of DR programs in emerging economies. These strategies deserve more attention as they represent some of the most cost-effective strategies to provide grid flexibility and avoid costs.

5. References

1. REN21. Renewables Global Futures Report 2013. Paris: REN21. 2013.
2. REN21. Renewables Global Status Report 2013. Paris: REN21. 2013.
3. Bloomberg New Energy Finance. Climatescope 2013: New Frontiers for Low-Carbon Energy Investment in Latin America and the Caribbean. 2013.
4. World Bank Development Indicators. Website: http://data.worldbank.org/data-catalog/world-development-indicators
5. Sustainable Energy for All Report (SE4ALL). Rapid Assessment and Gap Analysis Nicaragua 2013. Managua: SE4ALL. 2013.
6. Alta Consulting. Program Iceland – Nicaragua: Geothermal Capacity Building Project 2008-2012. Reykjavik: Alta Consulting. 2013.
7. Ministry of Energy and Mines. Website: http://www.minem.gob.pe/
8. Nicaragua's National Dispatch Center. Website: http://www.cndc.org.ni/
9. Fripp, M. SWITCH: A Planning Tool for Power Systems with Large Shares of Intermittent Renewable Energy. *Environmental Science and Technology*. **46**, 6371-6378. 2012.
10. Nelson, J., J. Johnston., Mileva, A., *et al.* High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. *Energy Policy*, **12**, 436-447. 2012.
11. Mileva, A., Nelson, J., J. Johnston, *et al.* SunShot Solar Power Reduces Costs and Uncertainty in Future Low-Carbon Electricity Systems. *Environmental Science and Technology*. **47**, 9053-9060. 2013.
12. Grayson, W.G. *Oil ad Mexican Foreign Policy*. Pittsburgh: University of Pittsburgh Press. 1988.
13. Meislin, R. 2 Latin Nations Act to Curb Oil for Belligerents. *The New York Times* (August 4th 1984). Website: http://www.nytimes.com/
14. Kinzer, S. Soviet Help to Sandinistas: No Blank Check. *The New York Times* (March 28th: 1984). Website: http://www.nytimes.com/
15. Kinzer, S. Sandinista says Soviet will meet amost all Nicaragua's needs. *The New York Times* (May 21st: 1985). Website: http://www.nytimes.com/
16. Pear, R. Bush to Seek $300 Million in Funds for Chamorro. *The New York Times* (March 13th: 1990). Website: http://www.nytimes.com/
17. Mostert, W. Easting Investment Barriers: Nicaragua's Renewable Energy Potential. *ESMAP: Knowledge Exchange Series*. **12**, 2009.
18. British Petroleum. Historical oil prices. Website: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy-2013/review-by-energy-type/oil/oil-prices.html
19. McGuigan. The Impact of World Bank and IMF Conditionality: An investigation into electricity privatization in Nicaragua. *Christian Aid Nicaragua*. 2007.
20. Mostert, W. *Unlocking Potential, Reducing Risk: Renewable Energy Policies for Nicaragua*. Washington D.C: ESMAP. 2007.
21. International Monetary Fund. Nicaragua: Enhanced Structural Adjustment Facility Economic Policy Framework Paper for 1999-2001. Website: http://www.imf.org/external/NP/PFP/1999/Nicarag/INDEX.HTM
22. International Monetary Fund. Nicaragua: Decision Point Document for the Enhanced Heavily Indebted Poor Countries (HIPC Initiative). 2000. Website: https://www.imf.org/external/np/hipc/2000/nic/nicaradp.pdf
23. Staten, C. *The History of Nicaragua*. California: ABC-CLIO. 2010.
24. Jacome, F. *Petrocaribe: The Current Phase of Venezuela's Oil Diplomacy in the Caribbean*. Friedrich Ebert Stiftung: 2011.
25. Casillas, C., Kammen, M.D. The Energy-Poverty-Climate Nexus. *Science*. **330**,1181-1182. 2010.
26. Gourdji, S. Craig, M., Shirley, R, *et al.* Sustainable Development Opportunities at the Climate, Land, Energy, and Water Nexus in Nicaragua. *Center for Latin American Studies Publications*. **No 33**. 2014.
27. Buren, A. Van. *The Woodfuel market in Nicaragua: the Economics, Sociology, and Management of a Natural Energy Resource*. Netherlands: CEDLA. 1990.
28. Erickson, J. Moving Mexico Back to Tap Water: Strategies to Restore Confidence in the Water System. *PolcicyMatters Journal*. Goldman School of Public Policy, UC Berkeley. 2012.
29. (Gleick 1994).
30. Economic Consulting Associates. *The Potential of Regional Power Sector Integration: Central American Electric Interconnection System (SIEPAC) | Transmission and Trading Case Study*. London: ECA. 2010.
31. CEPAL. *Estudio Sectorial Regional Sobre Energia y Cambio Climatico en Centroamerica*. Mexico: CEPAL. 2011.

32. Magrin, G., C. Gay García, D. Cruz Choque, J.C. Giménez, A.R. Moreno, G.J. Nagy, C. Nobre and A. Villamizar, 2007: Latin America. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 581-615.
33. World Watch Institute. *The Way Forward for Renewable Energy in Central America: Status Assessment, Best Practices and Gap Analysis*. Washington D.C: World Watch Institute. 2013.
34. Porras, M. E. *Twenty-Five Years of Production History at the Momotombo Geothermal Field, Nicaragua.* Reykjavik: United Nations University. 2008.
35. Global Power Solutions. *Nicaragua: Policy Strategy for the Promotion of Renewable Energy - Geothermal Energy Component*. Washington D.C: Global Power Solutions. 2006.
36. Torres, M. A. *Environmental Monitoring of Geothermal Projects in Nicaragua.* Reykjavik: United Nations University. 2011.
37. ECLAC. *Honduras: Assessment of the Damage Caused by Hurricane Mitch, 1998*. Washington D.C: ECLAC. 1999.
38. Perez, W.R. Las Canoas se Seca. *La Prensa* (2010). Website: http://www.laprensa.com.ni/2010/01/09/nacionales/12549
39. CEPAL. *Nicaragua, Efectos del Cambio Climatico sobre la Agricultura.* Mexico D.C: CEPAL. 2010.
40. Sitckler, M., Coe, M.T., Costa M.H. Dependence of hydropower energy generation on forests in the Amazon Basin at Local and Regional Scales. *PNAS*. 2013.
41. Cohen, J. Mesoamerica's Mystery Killer. *Science.* **344**, 143-147. 2014.
42. National Renewable Energy Laboratory. Wind Resource Map for Nicaragua (50 meter Wind). Website: http://www.nrel.gov/wind/pdfs/nicaragua.pdf
43. Friedman, B. Ardani, K., Feldman, D. Benchmarking Non-Hardware Balance-of-system (Soft) Costs for U.S Photovoltaic Systems, Using a Bottom-Up Approach and Installer Survey – Second Edition. *NREL Technical Report*. 2013.
44. Ernst & Young. RECAI Renewable Energy Country Attractiveness Index. **39**. 2013.
45. OPEN EI Nicaragua Hourly Solar Irradiation Data. Website: http://en.openei.org/wiki/Nicaragua
46. IAEA. Expansion Planning for Electrical Generating Systems. Vienna: IAEA 1984.
47. Lovins, A. *Reinventing Fire: Bold Business Solutions for the New Energy Era*. Washington D.C: Chelsea Green. 2011.
48. Abramsky, K. *Sparking a World Wide Energy Revolution* (Maegaard, P. Denmark: Politically Induced Paralysis in Wind Power's Homeland and Industrial Hub). Oakland: AKPress. 2010.
49. National Renewable Energy Laboratory. Wind Resource Atlas of Oaxaca. 2003.
50. Abramsky, K. *Sparking a World Wide Energy Revolution* (Oceransky, S. Fighting the Enclosure of Wind: Indigenous Resistance to the Privatization of the Wind Resource in Southern Mexico). Oakland: AKPress. 2010.
51. Abramsky, K. *Sparking a World Wide Energy Revolution* (Two mini case-studies: 1) The End of One Windmill Cooperative and 2) Chinese Peasants Killed in Land Conflict Over Windmills). Oakland: AKPress. 2010.
52. Abramsky, K. *Sparking a World Wide Energy Revolution* (Maegaard, P. An Authentic Story About How a Local Community Became Self-Sufficient in Pollution Free Energy from the Wind and Created a Source of Income for Citizens). Oakland: AKPress. 2010.
53. Sustainable Energy Solutions for Poverty Reduction in South Asia. Website: http://www.inseda.org/
54. Sistema BioBolsa. Website: http://sistemabiobolsa.com/en/
55. blueEnergy. Website: http://www.blueenergygroup.org/

6. Appendix: Further Exploratory Analysis

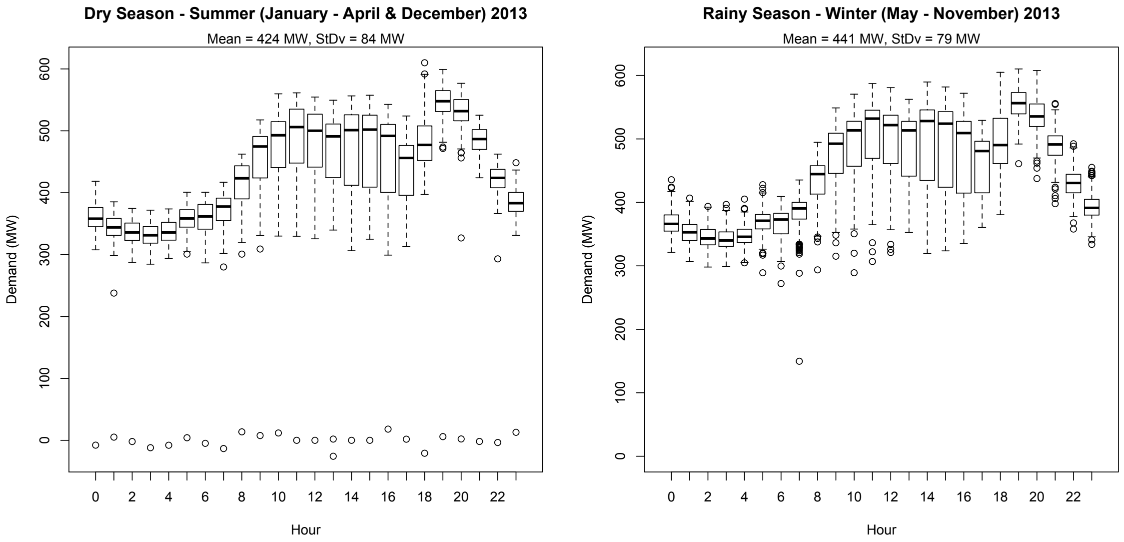


Figure 11. Boxplot of hour demand for the Dry and Rainy Seasons in Nicaragua (2013). There are no statistically significant differences (p≥ 0.10) in seasonal demand.

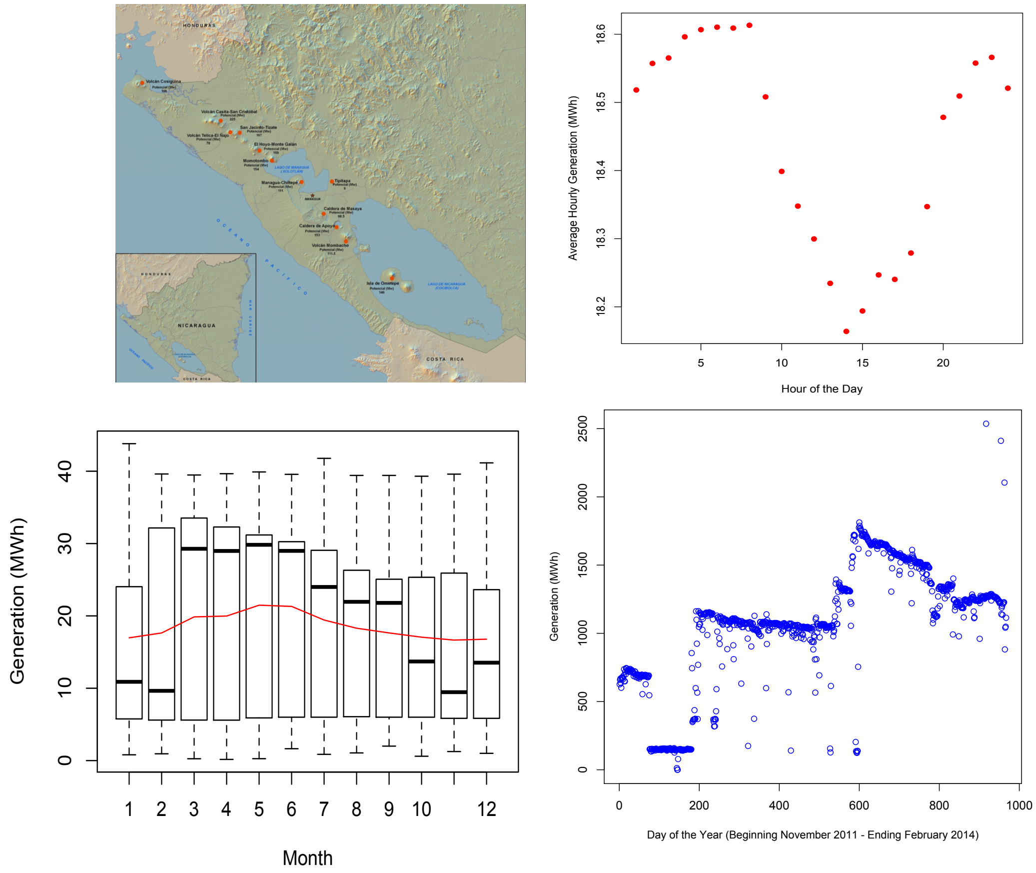


Figure 12. [A] *Map of Geothermal Areas in Nicaragua,* [B] *Average hourly wind generation (all plants, MWh),* [C] *Boxplot of monthly (hourly) hydro generation (inter-annual variability, MWh), and* [D] *Aggregate Daily Generation and Seasonal variability (July 2011 – February 2014).*

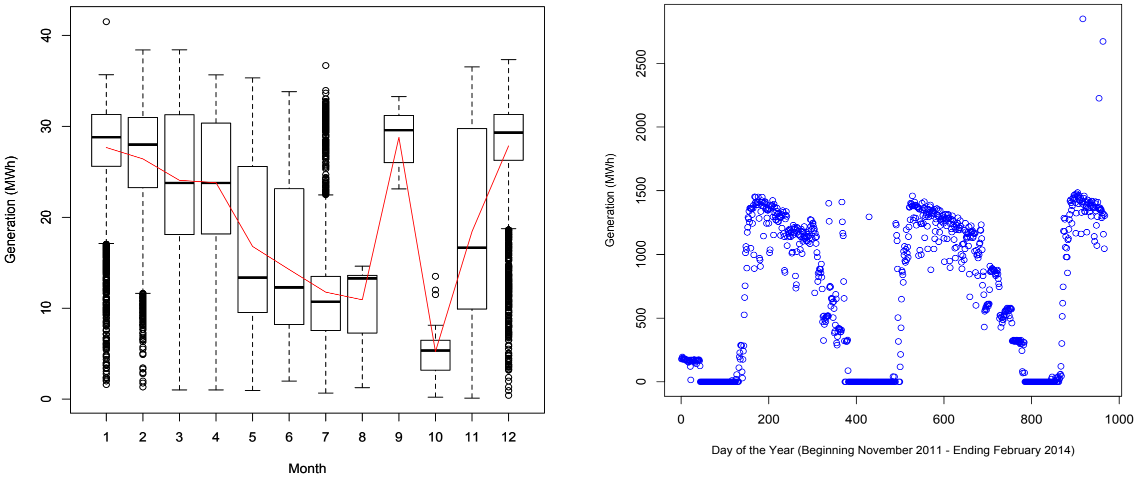


Figure 13. [A] Boxplot of monthly biomass generation (inter-annual variability, MWh), Nicaragua, and [B] Seasonal variability (November 2011 – February 2014).

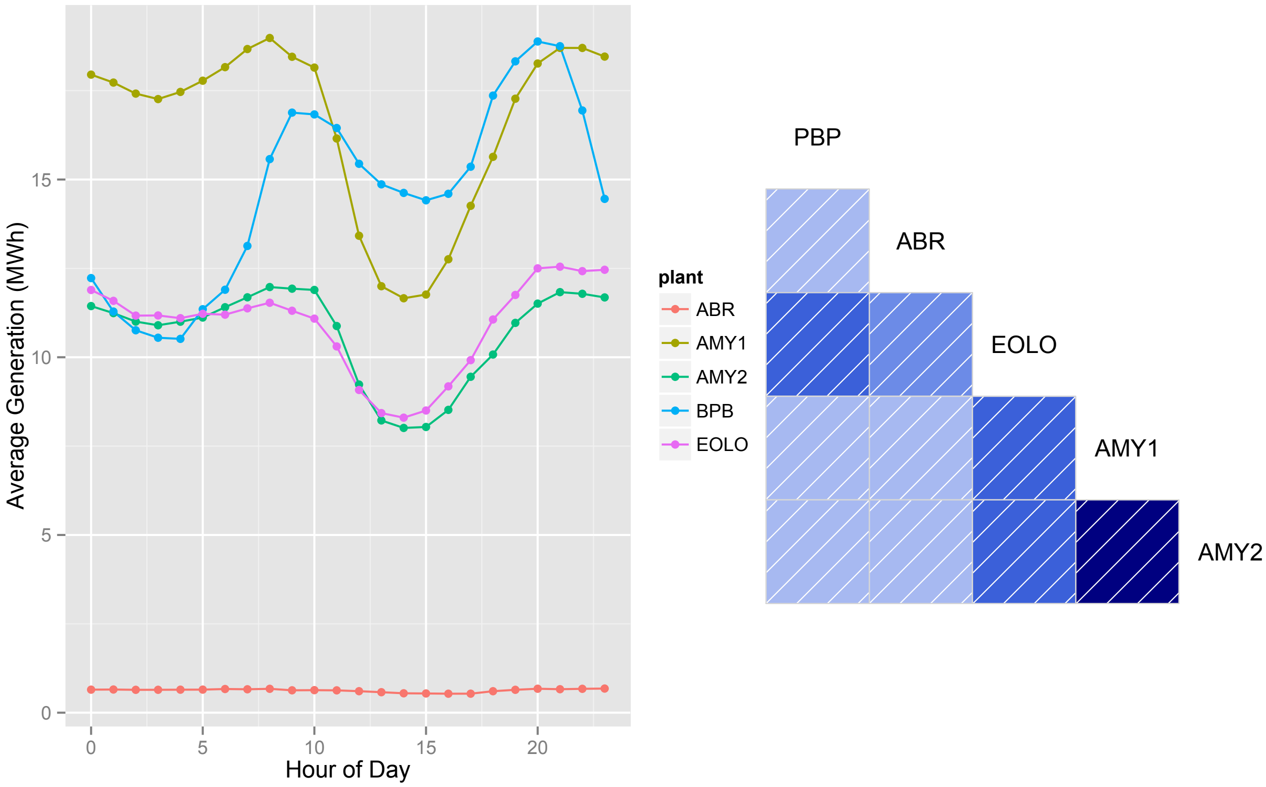


Figure 14. Average hourly generation by wind power plant [A] Map of Wind Potential in Nicaragua, [B] Hourly wind correlations by wind power plants (Dark Blue: 0.95, Blue: 0.8, Light Blue: 0.65, Very Light Blue: 0.5)

Solar Analysis

Average solar global irradiation in Nicaragua is 5.21kWh/m^2-day with the Pacific and Central part of the country receiving the most sunlight throughout the year. Global irradiation averages range as high as 5.7 kWh/m^2-day in Matagalpa, to as low as 4.6 kWh/m^2-day in Madriz. In terms of seasonal variability, February-May are both the hottest and sunniest months of the year, while the rainy season (June – November) has the lowest irradiation levels. Hourly solar irradiation data (global, horizontal and direct diffuse W/m^2) were obtained from Nicaragua's open EI database. Solar costs are obtained from the national renewable energy lab's (NREL's) analysis of the soft and hard costs of residential ($5.22/W) vs. commercial ($4.05/W) installations. These costs include total hardware, transaction, and supply chain costs, labor, permit fees, and indirect corporate costs. We also use costs from the first central grid-tied PV installation ($12W) in Nicaragua that was developed jointly by the Japanese International Cooperation Agency (JICA) and Nicaraguan Ministry of Energy and Mines.

Distributed rooftop generation is limited by the amount of available space for development throughout Managua. In the absence of detailed measurements or census data, satellite images may be used to quantify this constraint. A spatial analysis was conducted using Google Earth tools to estimate the total roof area in the city. First, a 0.25 km by 0.25 km area was analyzed as precisely as possible using tools to mark and measure areas assumed to be rooftops based on satellite images. Calculations revealed this area to be approximately 19.8% roof space, as shown in Figure 15. In order to scale this measurement to the entire urban area, a grid overlay was used to separate the city into 1 km by 1 km grid areas. These areas were then categorized based on their density relative to the representative area. The representative area was chosen in one of the densest parts of the city, so relative densities for other areas were 100%, 75%, 50%, 25%, and 0%. A map of Managua with relative densities marked is shown in Figure 15. For the 99 km^2 of Managua thought to have significant roof availability, a total of 13.4 km^2 of roof space was found to exist. Roof space available for solar development was conservatively constrained to half of the total roof area estimated.

Figure 15. Area of Managua analyzed to determine percent of roof space in the densest parts of the city. Analysis conducted using Google Earth [A], and Map of Managua with a 1km by 1km grid overlay. Each area is shaded to represent density relative to the densest area of the city. Red is 100% density, orange 75%, yellow 50%, and white 25%. Areas without significant roof area are not shaded [B]

First, a 0.25 km by 0.25 km area was analyzed as precisely as possible using tools to mark and measure areas assumed to be rooftops based on satellite images. Calculations revealed this area to be approximately 19.8% roof space, as shown in Figure 15. In order to scale this measurement to the entire urban area, a grid overlay was used to separate the city into 1 km by 1 km grid areas. These areas were then categorized based on their density relative to the representative area. The representative area was chosen in one of the densest parts of the city, so relative densities for other areas were 100%, 75%, 50%, 25%, and 0%. A map of Managua with relative densities marked is shown in Figure 15. For the 99 km^2 of Managua thought to have significant roof availability, a total of 13.4 km^2 of roof space was found to exist. Roof space available for solar development was conservatively constrained to half of the total roof area estimated.

Photovoltaic System Modeling

To connect panel rating to performance, a capacity factor is typically used. This metric quantifies the amount of energy produced each day per installed power capacity, and can be found by applying conversions to the rated panel power based on discrepancies between standard testing conditions (STC) and actual operating conditions. Solar panels are rated for the amount of DC power produced when perfectly clean, under 1kWh/m^2 of sunlight, and at 25°C. Therefore, conversions must be applied for DC to AC power inverter, dirt, and cell mismatch inefficiencies, actual sunlight exposure, and reduced performance under higher temperatures. Mathematically, this can be represented by:

$$E_{ac} = P_{rated} * E_{sun} * \eta_{inv} * \eta_{mismatch} * \eta_{temp} * \eta_{dirt} \text{ (1)}$$

Typical power rating for solar panels is 125 W/m^2, and typical inverter, dirt, and mismatch efficiencies are 0.9, 0.96, and 0.98, respectively. The average solar irradiation per day in Managua was found to be 5.4kWh/m^2 for the year of data analyzed. The average temperature in Managua during operating hours is 30°C, which translates to an efficiency of 0.81 [16]. The result of this calculation is that PV installations in Managua will, on average, generate 3.6 kWh of energy for every kW of installed capacity.

Linear Programming and Optimization and Scenario Analysis

We use linear programming to determine the amount of central vs. rooftop PV that could be developed to meet different levels of peak daily demand in Nicaragua. Our objective function attempts to minimize the cost of solar deployment:

$$\frac{min}{x_1 x_2} c_1 x_1 + c_2 x_2 \text{ (2)}$$

where c_1 (roof) and c_2 (central) are the costs per installed MW$_{ac}$, (\$/MW$_{ac}$) and x_1 and x_2 represent the installed capacity of rooftop and central PV (MW$_{ac}$). We constrain our model (in standard form) using non-negativity constraints, maximum available rooftop area (r_{max}), the maximum amount of installed capacity (central PV) for which there is available land area (c_{max}), and an equality constraint that ensures that we build enough capacity to meet a specific percentage of peak daily demand (D_{peak}):

Subject to

$$
\begin{aligned}
&-x_1 \leq 0 \qquad (3)\\
&-x_2 \leq 0\\
&a_1 * x_1 \leq r_{\max}\\
&x_2 \leq c_{\max}\\
&g_{roof} + g_{central} = D_{peak}
\end{aligned}
$$

Where g_{roof} and $g_{central}$ represent the total daily solar production (and area) required to meet a certain amount of demand. Cost coefficients are determined from NREL's reports on the soft and hard costs of PV deployment, we determine the maximum available rooftop area with the methodology provided above, constrain the amount of central PV to be installed to 150MW_{ac} (ten 15MW_{ac} plants), and iterate the percentage amount of peak daily demand that should be met through solar generation be from 5% (191 MWh) to 50% (1910 MWh).

Statistical analysis

We use the *sample correlation coefficient*, applied to the solar *X(k)* and wind *Y(k),* time series to evaluate the temporal correlation of solar and wind generation,

$$p_{X,Y} = \frac{\Sigma_k(X(k) - \bar{X})(Y(k) - \bar{Y}}{\sqrt{\Sigma_k(X(k) - \bar{X})^2}\sqrt{\Sigma_k(Y(k) - \bar{Y})^2}} \qquad (4)$$

and we later aggregate wind and solar output to evaluate the sample correlation coefficient between their sum and hourly average demand. We use the sample correlation coefficient, and correlation plots to evaluate whether or not solar generation could help smooth wind output variability. The correlation coefficient is 1 when the time series are perfectly correlated, and -1 when they are negatively (perfectly) correlated.

Optimization Results

We evaluate our linear program under two different cost assumptions. The first one uses rooftop and central PV coefficients from NREL, and the second uses a central PV coefficient from the first plant to be developed in Nicaragua. Our results suggest that, using NREL's cost assumptions, central PV alone could meet up to 15% of peak daily demand before reaching its capacity constraint (150MW_{ac} – 10 central PV plants). Beyond this level, rooftop PV would begin to be deployed until both central and rooftop PV can meet up to 50% of Managua's peak daily demand. On aggregate, rooftop and Central PV generation can meet over 50% of Nicaragua's peak daily demand without being constrained by rooftop area.

Our second scenario (central PV: \$12/MW_{ac}) suggests that no central PV would be deployed, and rooftop PV alone could meet from 5% to 50% of Managua's peak daily demand without reaching an area constraint. Figure 16 depicts the different combinations of rooftop and central PV that would be required to meet different levels of peak demand under both scenarios. Under both scenarios, if we assume that 10% of peak daily demand could be met using solar, costs would be approximately $US 420 million (all central PV), or $US 540 million (all rooftop) respectively.

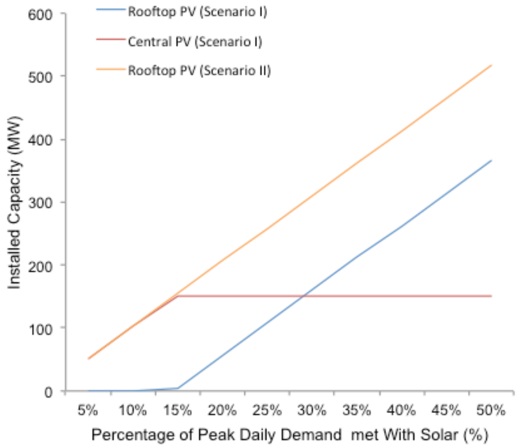


Fig. 16. Amount of rooftop and central PV installed capacity required to meet different levels of peak daily demand under two different cost scenarios (low and high central PV costs)

Correlation analysis

We use the assumption that 10% of peak daily demand can be met through solar generation (seven 15MW central PV plants) to evaluate the correlation between solar and wind output, and Managua's hourly demand. Plots of this correlation are shown in Figure 5. Our results suggest that there is no obvious smoothing effect from solar output for hourly ($p_{X,Y}$=p0.24), daily ($p_{X,Y}$=0.18), or monthly outputs ($p_{X,Y}$=0.42). That is, we don't find evidence to suggest that solar output could have a smoothing effect on wind intermittency (a strong negative correlation between wind and solar output would suggest the opposite). We also evaluate the sample correlation coefficient assuming storage could be available for all solar generated output from 8.00 am to 11.59 pm (~100 MWh), and find a negative correlation coefficient ($p_{X,Y}$=-0.23) when evaluating central PV generation (with storage) and wind output. When we evaluate the sample correlation coefficient between aggregate hourly wind and solar output, and hourly demand (with and without storage), we find a strong positive correlation ($p_{X,Y}$=0.50 no storage, $p_{X,Y}$=0.63 storage).

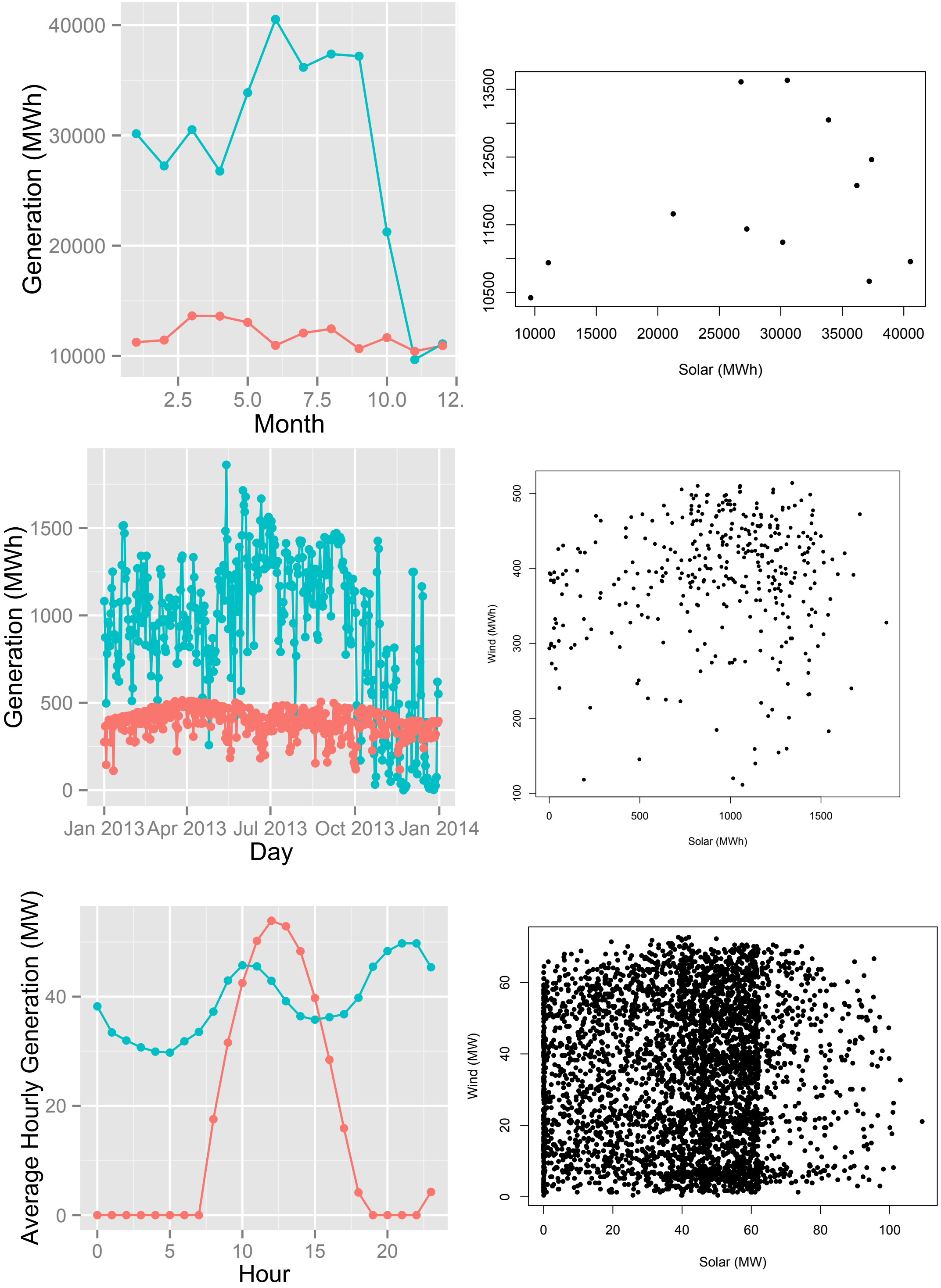


Fig 16. Monthly aggregate solar output (seven 15 MW central PV plants) and wind output: a) monthly, $\rho_{X,Y\ \mathrm{hourly}}$=0.24, b) daily $\rho_{X,Y\ \mathrm{daily}}$=0.18, and c) hourly $\rho_{X,Y\ \mathrm{monthly}}$=0.42)