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LETTER

Evidence and future scenarios of a low-carbon energy transition in Central America: a case study in Nicaragua

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Abstract

The global carbon emissions budget over the next decades depends critically on the choices made by fast-growing emerging economies. Few studies exist, however, that develop country-specific energy system integration insights that can inform emerging economies in this decision-making process. High spatial- and temporal-resolution power system planning is central to evaluating decarbonization scenarios, but obtaining the required data and models can be cost prohibitive, especially for researchers in low, lower-middle income economies. Here, we use Nicaragua as a case study to highlight the importance of high-resolution open access data and modeling platforms to evaluate fuel-switching strategies and their resulting cost of power under realistic technology, policy, and cost scenarios (2014–2030). Our results suggest that Nicaragua could cost-effectively achieve a low-carbon grid ($\geqslant$80%, based on non-large hydro renewable energy generation) by 2030 while also pursuing multiple development objectives. Regional cooperation (balancing) enables the highest wind and solar generation (18% and 3% by 2030, respectively), at the least cost (US\$127 MWh^{-1}). Potentially risky resources (geothermal and hydropower) raise system costs but do not significantly hinder decarbonization. Oil price sensitivity scenarios suggest renewable energy to be a more cost-effective long-term investment than fuel oil, even under the assumption of prevailing cheap oil prices. Nicaragua's options illustrate the opportunities and challenges of power system decarbonization for emerging economies, and the key role that open access data and modeling platforms can play in helping develop low-carbon transition pathways.

1. Introduction

Emerging economies on the verge of extended grid development are well positioned for low-carbon energy transitions, and Nicaragua, the third poorest country in the Western Hemisphere, is helping lead this transition in Latin America (Bloomberg New Energy Finance and Multilateral Investment Fund 2014). After decades of intervention from oil rich nations in its state affairs (Grayson 1988), prolonged periods of economic liberalization (1989–2006) (IMF 2000, Mostert 2007, Mostert 2009), and preferential oil agreements through the Bolivarian Alternative to the Americas (ALBA) and Petrocaribe (Jacome 2011), Nicaragua has recently begun transitioning to a post-petrol electric power grid motivated by energy security, industrial development, and financial risk mitigation.

In 2013 Nicaragua produced 40% of its electricity from non-hydro renewable energy and in 2014, on an hourly basis, it produced up to 50% of its generation from wind power alone (CNDC 2015). Between 2009 and 2014 it installed ~190 megawatts (MW) of wind energy capacity (14% of totaled installed capacity in 2014), underwent an intensive geothermal technical capacity training in partnership with Iceland, and received over US$ 1.5bn of cumulative renewable energy investments (2006–2014) (Alta Consulting 2013, CNDC 2015). Furthermore, Nicaragua has experienced this growth while continuing to make impressive progress in its rural electrification efforts (2.8% per year) towards the country's short-term goal of 87% electricity access by 2017. From Nicaragua having a poor track in electricity access in 2006 (54%), today the country has brought coverage to over 80% of its population (MEM 2015). Yet, despite this great progress and international accolades, the country's own renewable energy goals seem daunting (90% by 2020 including large hydropower) and increasingly uncertain in the midst of the short-term allure of historically low oil prices (Calero 2015, E&N 2015).

Recent research highlights that although low-carbon power grid transformations in emerging economies could prove challenging and expensive, cost-effective mitigation actions such as fossil fuel subsidy reform, decentralized modern energy access expansion and fuel switching in the power sector are not only possible, but feasible (Jakob *et al* 2014). In the near future, these countries are expected to both increase their contributions to and be greatly affected by climate change impacts (Magrin *et al* 2007, Field *et al* 2014, Ward and Mahowald 2014). However, acceptable economic growth may not require fossil fuel based energy (McKinsey and Company 2009). While some of the work that investigates low-carbon energy transitions within this context remains predominately hypothetical (Olbrisch *et al* 2011), to date little work has been developed to evaluate those emerging countries and regions that have already significantly moved towards developing low-carbon economies. While some individual countries across the world (for example, Denmark) have increasingly large penetrations of non-hydropower renewable energy, Central America has the highest penetration of non-large hydro renewable energy installed capacity (30%) in the Western Hemisphere (14% regional average) (Bloomberg New Energy Finance and Multilateral Investment Fund 2014, Bloomberg New Energy Finance/Multilateral Investment Fund 2012, 2013, WB 2015a, 2015b). The region includes environmental trailblazers such as Costa Rica, who is spearheading renewable energy generation efforts (non-large hydro renewable energy ⩽30 MW: 48% or 5 TWh) and tropical forest conservation and recovery strategies, and lesser known cases, such as Nicaragua, whose recent fuel-switching efforts have exceeded those of much larger economies in the region (Non large-hydro renewable electricity generation: Brazil 7%, Mexico 6%, Chile 9%) (figure 1) (Bloomberg New Energy Finance and Multilateral Investment Fund 2014, WB 2015a, 2015b).

In this paper we utilize both open access data and open source electric power system planning tools to demonstrate how low- and lower-middle income economies can develop optimal fuel-switching strategies and scenarios for a low-carbon grid. We choose Nicaragua for our analysis as it has relatively low electricity access (80%) (UNSE4ALL 2013), over 55% of Nicaragua's export revenue goes towards covering oil imports (UNSE4ALL 2013), and its current expansion plan (2014–2030) relies primarily on large hydropower development (MEM 2015), making the power system particularly vulnerable to hydro-climatological variability (Magrin *et al* 2007, Gourdji *et al* 2015). We evaluate eight power system planning scenarios: base case, geothermal and solar development mandates, oil and large-hydro moratoriums, expensive and risky geothermal resource development (higher exploratory and development costs with only half of the potential sites proving to be viable), cheap fuel oil prices, and a Central American regional interconnection) that can help Nicaragua evaluate different pathways for expansion of renewable and conventional generation technologies while achieving important development objectives (energy access, energy security, climate-risk mitigation and economic efficiency). The international energy agency and the intergovernmental panel on climate change (IPCC) provide a detailed discussion of many of the renewable energy technologies that are discussed in this analysis (International Energy Agency 2011, Intergovernmental Panel on Climate Change 2011).

Although scenario analysis allows us to explore a wide variety of optimal cost-effective options under a variety of fuel prices, technology costs, and policies, there are also other factors that must be considered when developing small- or large-scale infrastructure energy developments. Land-use ethics, environmental impact, energy return on energy invested, and public support are all crucial for the long-term viability of energy related infrastructural developments. We have not included these considerations in our analysis. In addition, we do not evaluate scenarios that explore grid-scale storage. To date no pumped hydroelectric storage sites have been planned in Nicaragua, and although grid-scale battery storage could well be an alternative for the country in the future, other strategies for renewable energy integration exist such as regional balancing and demand response (DR) that could prove to be more cost-effective. A detailed evaluation of the country's hydrogeology in relation to pumped hydropower storage, the impact of grid scale storage and the technical potential of DR in Nicaragua is something that will be evaluated in future work. Finally, because Nicaragua has not been found to have any promising fossil fuel reserves, and natural gas imports have not been discussed extensively in the country, we have left natural gas out of this analysis.

2. Data and methodology

We use SWITCH, an open source optimization model for planning power system investments and

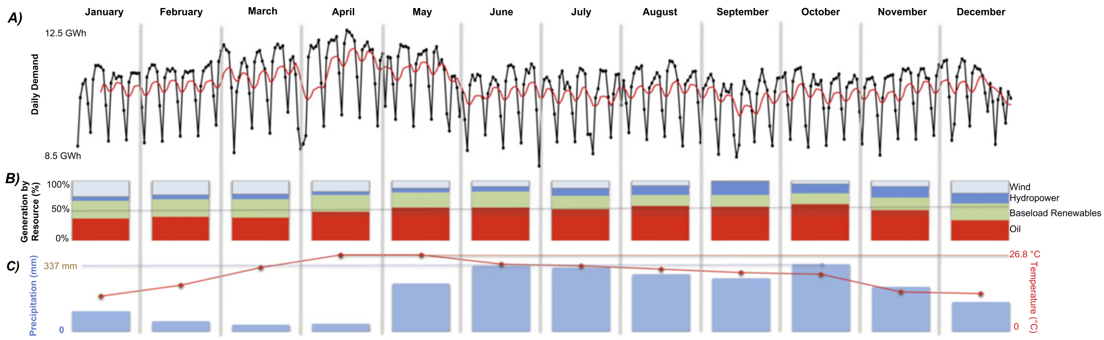

Figure 1. Demand and supply of power in Nicaragua (January–December 2013). (A) Daily demand (GWh) [red line represents a 10 day moving average], (B) Monthly generation by resource (%), and (C) temperature (°C: average 1990–2009) and precipitation (mm: average 1990–2009). March, April and May represent the peak electricity demand monthly aggregates in Nicaragua, closely tracking temperature increases during the same time period. Thermostatically controlled loads (refrigerators and air conditioners) use more electricity (or are used more intensively) at higher temperatures. Peak hydropower production occurs during the rainy season. Like the same figure for 2014 suggests (see supplemental information), a large-drought can have significant impact on hydropower production. Baseload renewables include geothermal and biomass resources.

operations, for investigating least-cost and low-carbon pathways for Nicaragua. SWITCH identifies generation investment plans that minimize the cost of delivering power, every hour, to every load zone in a country, subject to operational and policy constraints, while explicitly accounting for the hourly variability of intermittent renewable energy (Fripp 2012, Nelson *et al* 2012, Mileva *et al* 2013). Open access time-synchronized hourly national electricity demand (subdivided into sixteen load zones), hourly-generation profiles for every generating unit in the country, and spatio-temporal renewable energy resource potentials, in addition to power system costs (generation, storage, and transmission costs) are all used in this analysis.

Significant research cost and time savings were possible due to the open access nature of high-resolution (hourly) national electricity demand profiles, as well as power production (hourly) for every generation unit in Nicaragua (CNDC 2015). Electricity demand (national), generation, power system costs and information about the electric power system infrastructure were all open access and available since 2011. Barrier-free online access to high-resolution energy data enables researchers to focus on the development of analytical tools and methodologies for evaluating decarbonization, rather than on the time intensive and expensive processes that are often required for data acquisition.

2.1. Demand, generation, costs and electric power infrastructure

We use time-synchronized hourly historical national electricity demand and generation profiles (for every generation unit in the country) for Nicaragua from 2011 to 2014 to understand the temporal relationship between load and generation output levels (CNDC 2015). Hourly national electricity demand is disaggregated into sixteen load zones throughout the country using the relative monthly contribution of each load zone to the total. Hourly load data is scaled to future demand using official government projections, as well as national (hourly) and load-zone (monthly) historical growth rates. Hourly wind turbine output is obtained from historical values (2011–2014) of five different wind parks in Nicaragua, and this data along with wind resource potentials developed by the National Renewable Energy Laboratory are used to estimate hourly capacity factors for other potential wind projects across the country (National Renewable Energy Lab 2015a, 2015b). Average solar global irradiation in Nicaragua is 5.21 kWh m^{-2} d^{-1} with the Pacific and Central part of the country receiving the most sunlight throughout the year. 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. Solar hourly capacity factors were developed for the regions in the country with the largest potential using data from the United Nations Solar and Wind Energy Resource Assessment and 10km-resolution gridded satellite insolation data from the State University of New York (Open Energy Information 2015). All costs in the objective function, including power plant construction costs, are representative of values found in Nicaragua using information from official government sources (MEM 2015). We use an overnight cost declination rate to incorporate technological progress in all our potential generation projects. See supplementary materials for a more detailed explanation of system costs and power system infrastructure.

2.2. Open source power system planning tools and model description

There are several open source models that are extensively used for long-term electric grid and energy system planning. MARKAL/TIMES, MESSAGE, and the long-range energy alternatives energy planning system (LEAP), are some examples of energy system models that a variety of countries and regions across the world use in their energy related decision-making process. The degrees of 'openness', resolution of input data, and complexity of problem setup, however, vary by model. Take LEAP, for example, which offers the user a low barrier of entry by using a graphical user interphase and low initial data requirements to perform energy-system wide analysis, but offers relatively low-resolution output regarding the daily operation of a future electric grid (Heaps 2008). MARKAL/TIMES is also extensively used, and although its inputs and outputs allow for high-resolution community, multi-regional, and even global analysis, the model uses GAMS, a commercial software that can still be expensive to acquire and tedious to learn. Two other model interfaces are also necessary to create, browse, and modify input data and explore results (International Energy Agency Energy Technology Assistance Program 2005). Similarly, MESSAGE is a well-developed high-resolution modeling tool that has been used extensively across regions and institutions (for example, reports for the IPCC), and while the model has a variety of modules and interactive tools that increase its ease of use, the model itself is not readily accessible to the public (International Institute for Applied Systems Analysis 2013). Nicaragua currently uses a proprietary tool called OptGen, which specializes in modeling the least-cost expansion of multi-regional hydro-thermal systems, to develop a variety of future scenarios for its electric power grid (PSR 2015). We believe that the model's focus on hydropower and diesel generators is a key feature in observing drastically different electricity power futures as we observe in our results.

Within this vein, we use SWITCH, an open source capacity planning and dispatch model of the electric power sector. SWITCH is unprecedented in its use of high-resolution spatial and temporal data to realistically model power systems and plan long-term capacity expansion 30–50 years into the future (Fripp 2012, Nelson *et al* 2012, Mileva *et al* 2013). The SWITCH model is an improvement from previous electric power system models as it bridges two prevailing but largely separate methodologies in energy planning: the detailed evaluation of daily grid operations and costs under high penetrations of solar and wind generation, and detailed analysis on how the grid could be developed to achieve near- and long-term policy objectives at the lowest cost. The SWITCH model is open source, and has traditionally used open source tools such as Postgres SQL for arranging data inputs and outputs, but like other models, also uses commercial but widely used optimization packages (CPLEX/AMPL). Outputs and output summaries appear as text files and can be arranged and explored using a variety of open source tools including R and Python. The next version of SWITCH under development uses purely open source database management packages and optimization libraries built in Python.

SWITCH is formulated as a linear program whose objective function is to minimize the cost of meeting projected electricity demand (variable, fixed, O&M, and capital costs for generation, as well as transmission, distribution, and sunk costs) from present day until 2030, subject to policy, resource availability, reliability and generator output constraints. 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. Four four-year-long investment periods: 2014–2017, 2018–2021, 2022–2025, and 2026–2029, each containing data from 12 months, two days per month, and 12 h per day are used to investigate a range of expansion plans over the next two decades. 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 reflecting the remaining days in the month) to represent load and weather variability, as well as to ensure that the system is dispatching under typical load conditions, while incorporating capacity requirements for periods of high grid stress (Fripp 2012, Nelson *et al* 2012, Mileva *et al* 2013).

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 zones (Fripp 2012, Nelson *et al* 2012, Mileva *et al* 2013). Investment and dispatch variables are the two main sets of decision variables in SWITCH's 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 capacity of older plants to retire. Baseload (hourly power produced: generator capacity derated for forced and scheduled outages) and intermittent (hourly power produced: generator capacity x hourly capacity factor) power output is determined through capacity investment variables. Dispatch variables (all subject to capacity constraints set by investment decision variables) control the amount of power that can be generated from flexible generation and the amount of power to transfer along each transmission corridor. Hourly dispatch of generation and transmission are optimized simultaneously with investment decisions. A current limitation of SWITCH, however, is that it is predominantly a power system capacity planning and dispatch modeling tool that does not evaluate the entirety of the energy system. While additional modules have begun to be developed (biomass and electric vehicles modules, for example) (Sanchez *et al* 2015), much work remains to be done to ensure that additional modules are consistent with the model's goal of marrying the development of high-resolution daily (and hourly) analysis for operational purposes with long-term system planning. Detailed model description, descriptive statistics and additional results are presented in the supplementary materials.

3. Results

The base-cost scenario (business as usual (BAU) oil prices US$80/bbl ∼ increasing 2% per year), results in a least-cost system that obtains 39% of its power from oil in the first time period (2014–2017), and only 21%, 2% and 4% in the subsequent time periods (figure 2). The role that fossil fuel-generators (oil and diesel) play in the energy system also changes over time as they become more useful (and cost-effective) for their dispatchability (and ability to compensate for variable renewable output) rather than baseload generation. In the final time period, oil generators provide 27% and 99% of all spinning and quickstart (10 min) reserves respectively. Spinning reserves refer to generators (and generation capacity) that are 'on-line' but unloaded and can respond to grid conditions within 10 s (frequency response) and 10 min (generation and transmission outages, for example). Only grid-scale diesel powered district-wide plants are used in our analysis. Tumarín, Nicaragua's largest proposed hydropower project, is built in the third time period (2022–2026), but not developed to its full potential (only 118 MW, or 47%, out of 253 potential MW are built). By the final time period, hydropower provides approximately 65% of the system's spinning reserves, despite the resource's operational availability being mainly used for generation (86%), rather than ancillary services. Ancillary services refer to those services that help support the continuous flow of electricity throughout the grid. They may include frequency control, spinning and operating reserves, scheduling and dispatch, reactive power and voltage control, loss compensation, load following, system protection, and energy imbalance management services. Under the assumption of low-risk geothermal investments ($US 4 W^{-1}) (all geothermal sites prove to be viable and cost-effective to develop), the resource proves to be one of the most cost-effective system investments, providing approximately 20% of the power in the first two time-periods, but over half the power afterwards. Construction of 91% of geothermal potential is started immediately, bringing that capacity online by the beginning of the third time period (2022). The remainder of the capacity is brought online by the beginning of the fourth time period. While geothermal energy could potentially be a promising and cost-effective investment in Nicaragua, the country's geologic characteristics and technology choices will prove to be determining factor for the resource's long-term sustainability (UCS 2015, Kagel *et al* 2007). Only two additional wind projects are developed in this scenario (beyond Nicaragua's installed wind capacity in 2013), providing 12% of power by the final time period. Not all potential wind projects are developed because their costs are greater than alternatives. Wind costs do not change significantly over time because it is a relatively mature technology, but solar costs do decline by our assumptions. Central PV generation, which is currently undeveloped in Nicaragua, provides 3% of power during the final investment period. Land constraints and renewable energy generation limits within each load zone hinder central PV expansion, in addition to the fact that the resource competes with other quality renewable resources such as geothermal (base load) and wind (high capacity factor). Conventional and renewable resources are all developed in the areas with least cost and greatest potential (figure 3). Absent any explicit carbon or renewable energy policy, this base case scenario achieves a renewables based power system (81%—without including large hydropower and diesel generators) at a power cost of US $128/Megawatt-hour (MWh). This power system also achieves exceptionally low CO_2 emissions (non life-cycle, generation related emissions), emitting 4.7 Megatons CO_2 (MtonsCO_2) in the first time period, and only 0.81 MtonsCO_2 by the end of the analysis (note: metric ton). Currently, Nicaragua emits 4.7 MtonsCO_2 per year (WB 2015a, 2015b). A more detailed discussion on costs is provided in the supplemental information.

Our scenario analysis explores three main themes around a power system's evolution: *changing price dynamics* (specifically for fossil fuels and central PV), the inherent exploratory and development *risk* of certain resources (geothermal: exploration and resource development, large-hydropower: hydro-climatological), and *renewable energy policy mandates*. Changing price dynamics scenarios explore BAU (US$80/bbl ∼ increasing 2% per year) and cheap oil prices (US$50/bbl ∼ increasing 2% per year), as well as BAU (US$2 W^{-1}) and cheap solar prices (US$1 W^{-1}) (figure 4). A high-risk geothermal exploration and development scenario ($7 W^{-1} instead of $4 W^{-1} where only half of Nicaragua's potential geothermal projects are considered viable), and a scenario where the grid's vulnerability to hydro-climatological variability is minimized (hydropower representing only 5% of the total generation by the final time period) explores the grid cost impacts of potentially risky system investments. We consider policy impacts through the implementation of solar and geothermal mandates, each providing 25% and 30% of total energy by 2030 respectively, as well as the deployment of a 300 MW interconnection across Nicaragua's borders (both to Honduras and Costa Rica) (figure 2).

Results suggest that under BAU oil price dynamics, a geothermal mandate (currently Nicaragua's most promising undeveloped resource) would give similar results to the base case; suggesting that even without policy implementations geothermal energy is one the

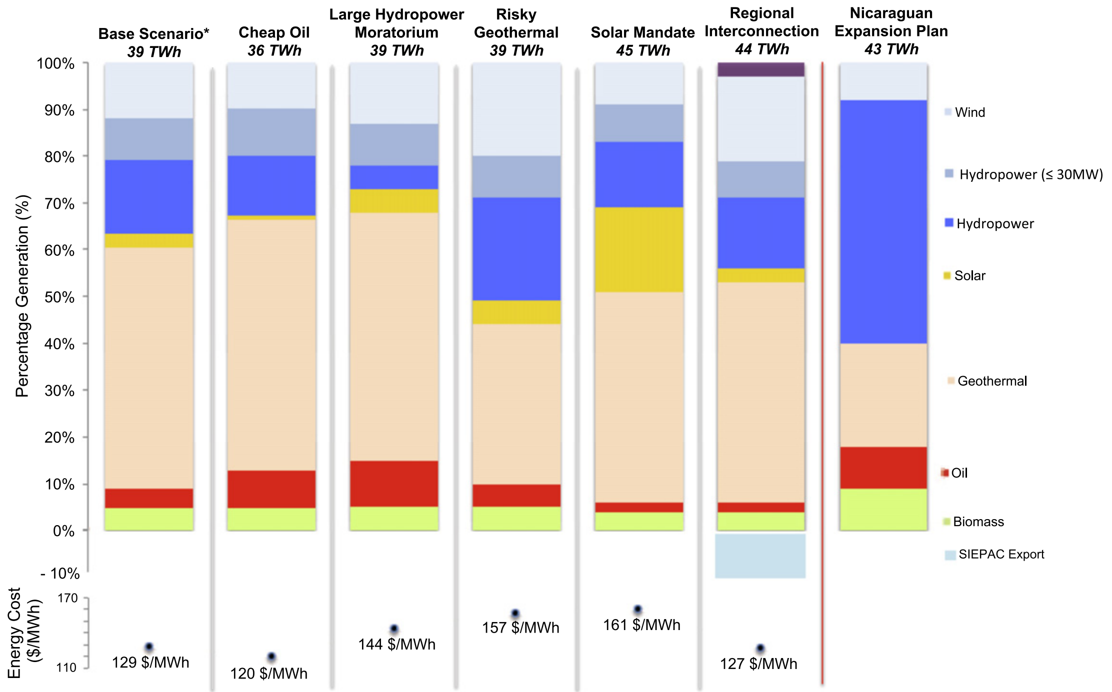

Figure 2. Generation (%) by fuel type in the final time period (2026–2030; total system load is 32 TWh for each scenario). End-scenario (2026–2030) results suggest that even without implementing strong renewable energy integration policies, development of renewable energy in Nicaragua (Geothermal, Wind and Solar) represents some the most cost-effective energy system investments (Base Scenario). Spilled energy (~9 TWh) is largest with a solar mandate, and smallest in the cheap oil scenario (~1 TWh). Spilled energy refers to power production that is not used due to technical reasons, such as insufficient transmission capacity. *Policy Implementations*: a solar mandate (25% of all generation by 2030) raises overall system costs to the highest of any scenario. *Risky Resources*: if only half the geothermal projects were developed, and exploration and development cost were almost twice as expensive as expected ($7 W^{-1} instead of $4.5 W^{-1}), system costs would be 12% higher than the base case, with additional investments going towards wind and large hydro. A system that is less vulnerable to hydro climatological dry shocks (hydro moratorium), is more resilient, but also more expensive. *Price Trend*: cheap oil prices (US$50/bbl ~ increasing 2% per year) increase the use of oil, but do not significantly hinder decarbonization. *Cooperation*: a regional interconnection, here modeled as import and export of power with Honduras and Costa Rica adds grid-flexibility, and allows for the most cost-effective penetration of intermittent renewable energy into the grid. Import–export dynamics in the interconnection scenario depend on price assumptions between Honduras, Nicaragua and Costa Rica. Our results are notably different from Nicaragua's expansion plan, which uses a modeling framework that optimizes the use of hydropower and thermal energy. Note: implementing a geothermal mandate gives very similar results to the base case (see text for details).

most cost-effective system investments. The proximity of potential geothermal projects to existing power system infrastructure, its bountiful resource potential (1000 MW are considered economically viable geothermal) (Mostert 2007), and its ability to provide baseload power (referring to the resource's ability to consistently generate power to satisfy minimum demand) all favor its development without policy interventions. On the other hand, a BAU solar mandate is the most expensive scenario (US$161 MWh^{-1}), experiencing the highest capital costs, as well as the second largest spinning fuel cost expenditures (the largest spinning reserve fuel costs are experienced through a reduction in hydropower output, detailed below). Under a high penetration of intermittent renewable energy, spinning reserves are used to respond to contingencies such as unscheduled power plant or transmission line outages, as well as to respond to small, random fluctuations around normal load (Hummon *et al* 2013). Enabling a regional interconnection allows for the most cost-effective (US $127 MWh^{-1}) use of intermittent renewable energy (22%), the lowest oil consumption (2%), and the lowest excess curtailment (5%). The interconnection is modeled here as simple markets with power transfer limits of 100 MW in either direction and flat clearing prices between $350 and $100 per MWh for Costa Rica and Honduras. Costa Rica and Honduras are connected to Nicaragua's grid at southern and northern load zones based on transmission maps. The optimization has a choice of buying or selling power to either country at their respective clearing prices. Beyond the ability to opportunistically buy and sell power in a regional market, an interconnection can also lead to avoided capacity, fuel, and operation costs. While this vision is almost a reality with the end of 2014 seeing the completion of the Central American Electricity Interconnection System (SIEPAC) transmission network, a carefully developed power pool, market mechanisms and rules must be developed (and followed) to truly foster regional cooperation. Across Central America countries have continued making

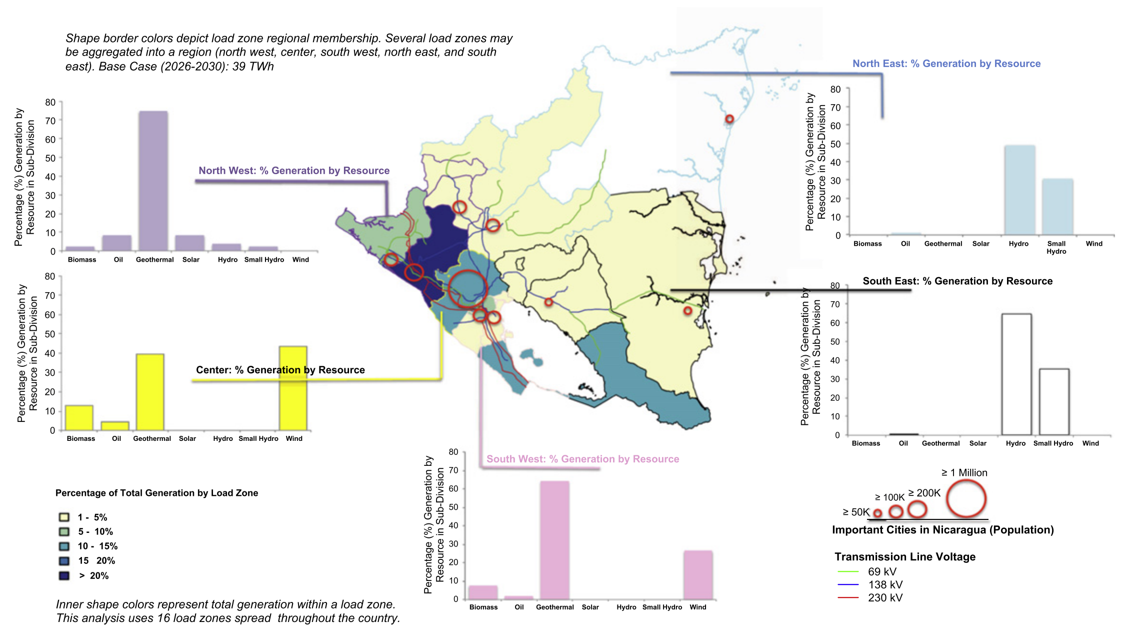

Figure 3. Spatial distribution of system investments in the base case scenario (2026-2030: 39 TWh). In the final time period of the base case scenario, as it is with all other scenarios, SWITCH optimizes the spatial use of conventional and renewable resources. Due to the proximity of major load centers to energy production and electricity infrastructure, most energy is produced and consumed locally. Nicaragua's Pacific (west) coast contains the vast majority of renewable resource potential (geothermal, wind and solar) in the country, and thus most generation projects are located in this area. Geothermal and wind energy deployments are some of the most cost-effective system investments not only because their large potential, but also due to their proximity to the country's most important population centers (red circles) and accompanying power system infrastructure. Boundary divisions (line colors: purple, yellow, light pink, light blue and black) represent generation diversity in different areas of the country (north west, center, southwest, southeast, north east). Inner departmental colors (dark blue to white) represent a load zone's contribution to total generation. In SWITCH, renewable resources compete with each other for space (land constraints) as well as maximum renewable energy generation limits within each load area.

power grid infrastructural improvements to increase system reliability, reach universal energy access targets, and further the penetration of uncertain and variable energy into the grid. In Nicaragua, for example, the National Sustainable Electrification and Renewable Energy Program Plan (PNSER) has made significant progress in recent years with regards to rural electrification, transmission expansion, and system wide upgrades.

The results from a high-risk geothermal case and a large-hydro moratorium produce the second and third largest system costs (US\$157 MWh^{-1} and US \$145 MWh^{-1} respectively), as geothermal becomes almost twice as expensive (baseload), and oil becomes a more cost-effective investment to match intermittent renewable energy output (instead of hydropower). Geothermal and hydropower can represent risky investments, but in different ways. Regional climate change models of Central America suggest that hydropower will be increasingly affected by a reduction of rainy days (more dry years), an increase in the frequency and intensity of extreme wet events, as well as increased silting (Magrin *et al* 2007, CEPAL 2011). In 2010 the country saw its first hydropower station ('Las Canoas') go dry due to a combination of a deep and prolonged drought and water use conflict between rice farmers, residential areas, and power production (Perez 2010), and 2014 brought one of the worst droughts in over 30 years, affecting livestock, agricultural producers, and hydropower (28% drop in hydropower production, year-to-year variability without taking into account a new hydropower plant that came online in 2013) (Flores 2014). Additionally, and despite the country having made progress towards a better use of geothermal resources, Nicaragua has a history of wells being overexploited and sub-optimally operated (Global Power Solutions 2008, Porras 2008). The wells being located in protected areas increases the complexity of the resource's development (Torres 2011).

Cheap oil prices change investment dynamics but do not significantly hinder decarbonization (figure 4). Under current oil price dynamics (US\$50/bbl), but expecting the price to increase again over time (2% per year), the system doesn't make any solar investments until the last period, but still reaches a system that is predominantly based on non-large hydro renewable energy (80%). Even in a scenario where prices would continue dropping from US\$50/bbl (2% per year), the system is still predominantly low-carbon. Cheap central PV generation (US\$1 W^{-1}—which is consistent with current price trends) (Zheng and Kammen 2014, Mileva *et al* 2013) leads to an energy system where most solar investments (and the highest solar generation) occur in the first time period, but its deployment is hindered by cheap oil prices (even on a cheap solar

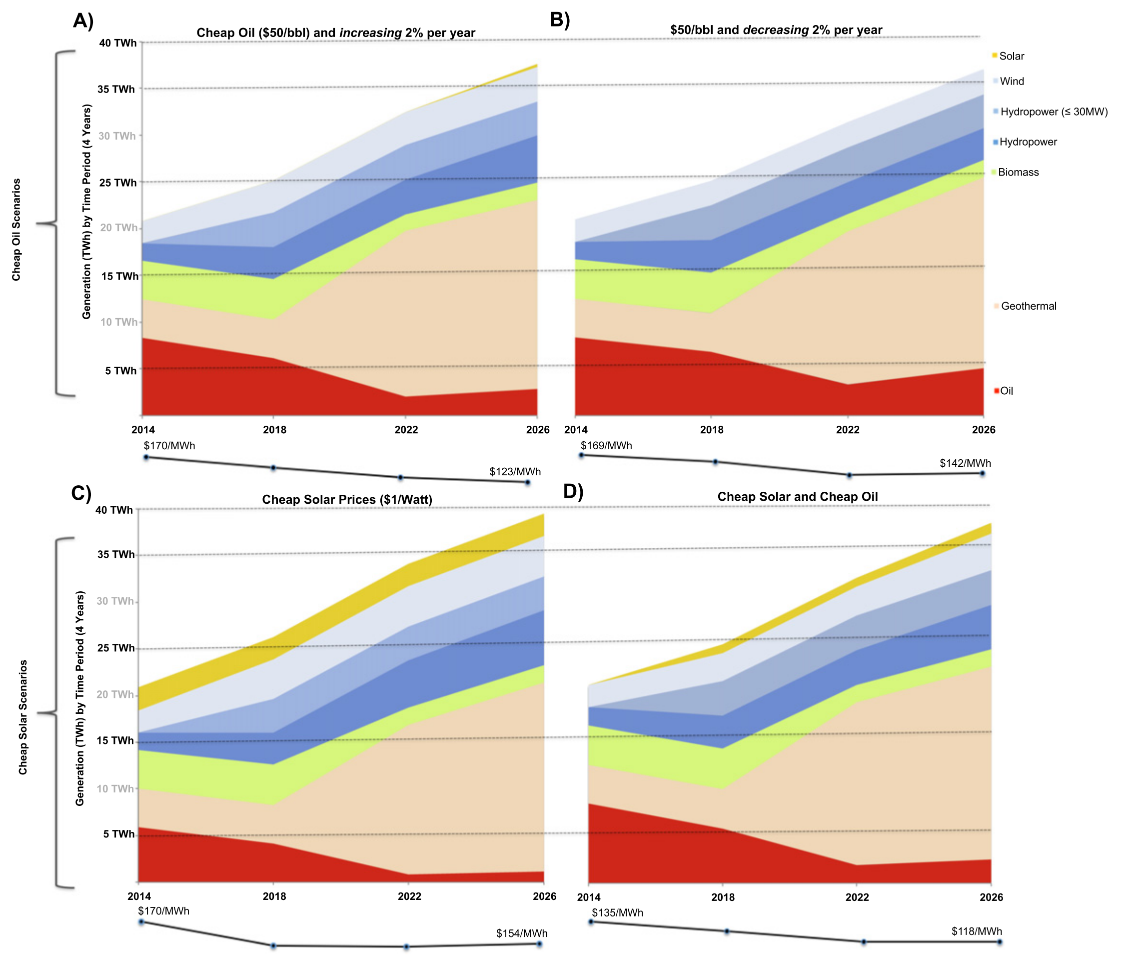

Figure 4. Energy mix by investment period and scenario. Cheap oil scenarios: (A) and (B) depict the 'base case' scenario under the assumption of cheap oil prices (US\$50/bbl) increasing (2% per year) and decreasing (2% per year) oil prices. We find that although oil fuel based generation increases with cheap oil prices, this does not significantly hinder decarbonization. More oil price scenarios are explored in the supplemental information. Cheap Solar Prices ($1\ W^{-1}$): under an assumption of cheap solar prices (C) and (D), the system makes central PV investments in the first time period, but the contribution of solar decreases over time as geothermal projects eventually come online. Under a scenario of prevailing cheap oil prices, central PV generation is displaced despite its price competitiveness (\$US1 W^{-1}). Although highly unrealistic, cheap PV technology and oil prices result in the lowest system costs for the base case (US\$188 MWh^{-1}). Central PV price sensitivities are further explored in the supplemental information.

scenario). Dynamic price scenarios are explored further in the supplemental information.

4. Summary and discussion

There are many lessons that emerging regions can draw from Nicaragua's transition to a low-carbon power system. The technical challenges that emerge from a high-renewables penetration grid will require the system to employ tools and strategies that make it more reliable, and will require market and regulatory frameworks to evolve in parallel. It is crucial that energy planning capacity expansion models are developed to study entire regions as integrated cooperating entities, rather than single balancing units. These trans-national regional integrated assessments are crucial for avoiding excess capacity and enabling cost-effective renewable energy integration, particularly for emerging economies seeking to optimize resource use and economic efficiency. A more responsive and automated energy system will also need to be developed. Power dispatch models that can accurately incorporate day-ahead weather forecasts for wind speeds and solar insolation, as well as more accurate demand predictive models are all necessary in realizing cost-effective and large-scale integration of wind and solar energy.

While we believe Nicaragua to have made significant progress in enabling an electric power grid transition, our results suggest significant differences with the country's current expansion plan (little emphasis in geothermal and solar developments, and a continued overdependence on oil), and areas where the country could do more to reduce its dependency on oil imports, and begin the transition to a low-carbon economy. First, the theoretical potential of solar and geothermal energy needs to be further explored and realized. An enabling framework for solar that considers net metering, feed in tariffs, value-of-solar tariffs, solar 'carve outs', tax incentives and subsidies have all proven to be incredibly successful in other countries (Rogers and Wisland 2014). For large-scale PV in particular, distributed generation goals inscribed within renewable energy targets and permitting reforms (reducing the cost and time in the permitting process) are key for the future growth of the resource (Rogers and Wisland 2014). Similarly for geothermal energy, regulatory processes must be amended and innovative financial schemes must be developed. Historically beneficial policies that have supported the growth of the geothermal resource elsewhere include tax incentives, subsidies for studies regarding exploration and resource development, resource generation targets, clearly defined leasing and permitting policies, and greenhouse gas reduction regulations (National Renewable Energy Lab 2011, National Renewable Energy Lab 2015a, 2015b).

Evaluating the potential for demand response (DR) is another immediate action that must be investigated by the actors enabling an energy transition. DR can help avoid future installed capacity costs, contribute to peak shaving, and reduce the need for contingency and regulatory reserves. A market for ancillary services, however, is fundamental for the long-term cost-effectiveness for a renewable energy based grid and must be developed in tandem to studies that explore DR technical potential, and Nicaragua will have to use other region's examples (California and or Denmark, for example) to guide its own process (CAISO 2007, Kristiansen 2007). Finally, and with personal transport playing an increasingly large role in Nicaragua's total final energy consumption (transportation accounts for 30% of total final energy consumption), the country must begin evaluating how it will begin reforming energy consumption in its transport sector. While alternative fuels for transportation could prove to be a viable strategy, pilot projects investigating the potential for electric vehicles (private and public transport vehicles) to reduce gasoline consumption and provide ancillary services for wind integration should be supported. The Philippines with the eJeepney and Uruguay's public transport electric vehicle efforts to electrify transportation are examples of middle-income economies piloting initiatives to pursue energy independence while decarbonizatizing their energy system (eJeepney 2015, Melgar 2015). Many of these actions require both in-depth analysis and technology pilot deployments to evaluate potential and retrieve data. There is no doubt that the region's energy future will be shaped by renewable energy, and Nicaragua would surely continue being a regional leader if it implemented and realized several of these recommended actions.

Open access data is central to envisioning alternative pathways to extended grid development, exploring a panoply of renewables based generation scenarios, and evaluating cost-effective integration strategies. In Nicaragua, open access grid data has enabled North–South research collaborations, has helped in the development of 'in country' institutional partnerships, and increased the cost-effectiveness of renewable energy related and electricity grid based research. Open access data significantly reduces the time intensive barriers that exist for accessing massive datasets by removing the need for extensive paperwork requirements and bureaucratic processes that can often be crippling for researchers. Accessing renewable resource potential and grid related data can often also be very expensive, both in the labor hours required to navigate bureaucratic processes, and the actual cost of data, which can reach the tenths of thousands of dollars. The value of open access data for a country, then, is one that builds on itself as it becomes much easier to replicate analysis, present counterfactuals to prevailing paradigms, and establish long-term productive collaborations. Beyond descriptive analysis, a choice of open source models exists that can then be used for energy system long-term planning, scenario analyses, and design of decarbonization pathways.

Across the world, many low-, lower-middle, and upper-middle income economies, as well as entire regions, are entering a post-petrol power system transition. Honduras will soon be developing over 80 MW of central PV, and the United States has expressed financial commitment to furthering sustainable energy investments in Central America. Just in a few years from now Uruguay is expected to be able to produce 35% of its generation from wind alone (2016), Kenya will see 300 MW of wind come online (2016), Thailand will develop 3 gigawatts (GW) of rooftop and village based solar projects (2021), and Africa's Clean Energy Corridor should open the door for a new wave of clean energy investments. The reasons and decision-making progress for power grid transformation, however, always vary by country, region, and are almost always context specific. Security of supply (energy security and economic efficiency), climate change mitigation, and air-pollution reduction all figure prominently but at varying degrees of importance as key drivers for energy system transformations (McCollum *et al* 2011). Although these objectives are often intertwined, evidence suggests that they often compete against each other when making long-term energy system investments: energy security and air pollution are considered near-term issues (i.e., inter-decadal, next two decades), while climate change is often viewed as a mid- to long-term problem (i.e., 2030 and beyond) (McCollum *et al* 2011, Zimmer *et al* 2015). While some research suggests that focusing primarily on climate change mitigation delivers on multiple objectives (energy security and air pollution) in comparison to focusing on energy security and pollution alone (McCollum *et al* 2011), it is unclear if low oil prices could derail a low-carbon energy transition for countries like Nicaragua. Our analysis suggests that a high penetration renewables based grid (wind, geothermal, biomass, and small hydropower) is still costcompetitive under multiple low-oil price assumptions (see supplementary materials).

As funding for renewable energy shifts decisively towards emerging economies, resource potential studies must be accompanied by research regarding flexibility requirements, and most importantly, regional integration (balancing). Trans-national cooperation could be one the most cost-effective system investments for emerging economies transitioning into a post-petrol society. Extending this analysis to the rest of Latin America, and other regions in the world, would likely show that with current technological breakthroughs, and even with current (and perhaps future) relatively low-oil prices, low-carbon power grid transitions (further enabled by regional cooperation) are both cost-effective and technically feasible. With the global carbon emissions budget over the next decades depending critically on the choices made by fast-growing emerging economies (Chakravarty *et al* 2009, Raupach *et al* 2014), it is increasingly important to develop studies like this one to envision alternative low-carbon development pathways (Olbrisch *et al* 2011, Schmidt *et al* 2014).

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Author contributions

DP, JJ and DMK conceived the work. DP and JJ designed and implemented the analysis, and DP was lead author. DMK, DC and MVM contributed valuable reviews and feedback.

Competing financial interests

The authors declare no competing financial interests.

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