July 2019

Renewable Energy Access and Resilience in Urban Developing Areas: Distributed Solar Networks and Peer-to-Peer Energy Trading in Puerto Rico

Pascale Bronder
Yale University

Renewable Energy Access and Resilience in Urban Developing Areas: Distributed Solar Networks and Peer-to-Peer Energy Trading in Puerto Rico

Pascale Bronder

Environmental Studies and Energy Studies
Advisor: John Wargo

Grace Hopper College | Yale University
April 12, 2019

<u>Table of Contents</u>

Glossary

EIA.. U.S. Energy Information Administration
EPA... U.S. Environment Protection Agency
FEMA... U.S. Federal Emergency Management Agency
GW... Giga-Watt (10^9 watts)
HVAC.. High Voltage Alternative Current
HVDC... High Voltage Direct Current
kWh.. kilo-Watt-hour (10^3 watts * 1 hour)
MW... Mega-Watt (10^6 watts)
NGO.. non-governmental organization
NOAA.. U.S. National Oceanic and Atmospheric Administration
OECD................................... Organization for Economic Co-Operation and Development
P2P.. peer-to-peer
PPP.. public-private partnership
PPA.. power purchase agreements
PREPA... Puerto Rico Electric Power Authority
PV.. photovoltaic
RMI.. Rocky Mountain Institute
SGDs.. Sustainable Development Goals
TC.. Transmission Center
UN... United Nations
UNFCCC................................. United Nations Framework Convention on Climate Change
WEF.. World Economic Forum

Introduction

Innovations in air quality monitoring saves lives. Starting with canneries in coal mines, a traditional method to identify and warn against toxic gases, countless human lives were spared throughout the 1800s and 1900s.[1] With the introduction of Drager tubes in the 1930s, photoionization detectors in the 1970s, and air quality monitors equipped with sensors, GPS, digital readings, and more all at a lower cost since then,[2] the technological advancements improved understanding of correlations between pollutant concentrations and health effects, among other discoveries. The United States Environmental Protection Agency (EPA) held a workshop to evaluate the accuracy and trajectory of air quality monitoring, predicting that in the near future, every person would be able to participate democratically in air quality data collection that could prove a great resource for researchers, health professions, individuals, and policy makers.[3] The history of air quality sensors is just one example of how new technology improves climate science and helps inform the public and major decision makers about key environmental and health factors. Technology goes hand in hand with science. Exploring the environmental applicability of cutting-edge technologies could propel renewable energy development and efficiency efforts and contribute to the improvement of solutions to fight climate change.

Populations and industries have long utilized innovative technologies to improve existing systems. One of the most innovative technologies that applies to renewable energy systems and can create system-wide change right now is blockchain technology. With intense energy disparity globally and natural disasters like Hurricanes Maria and Harvey exposing the vulnerability of electric grids, resiliency of energy systems is a key target field for improvement. Since the 1973 embargo that blocked Middle Eastern oil imports into the United States, energy security became a household issue

[1] Eschner, Kat. "The Story of the Real Canary in the Coal Mine." *Smithsonian.com*. December 30, 2016. Accessed December 2018.
[2] Dye, Timothy. "A Brief History of Air Quality Sensors." *TD Environmental*. 2017. Accessed 2019.
[3] Vallano, D., E. Snyder, Vasu Kilaru, E. Thoma, R. Williams, G. Hagler, Watkins, T. "Air Pollution Sensors: Highlights from an EPA Workshop on the Evolution and Revolution in Low-Cost Participatory Air Monitoring." *Air and Waste Management Association* (2012):38-33.

has been a key pain point for many politicians.[4] Daniel Yergin, a leader in energy and geopolitics, writes that energy security first became a "question of national strategy" when Winston Churchill transitioned the entire British Navy fleet from coal to oil.[5] The switch made British ships faster than those of the Germans right before World War I, however replaced the stable source from Wales to insecure supplies from Persia.[6] Resilient energy, particularly in the case study of Puerto Rico after the hurricanes, predominantly looks like energy independence. Independence of energy use comes from ownership and diversity of energy sources. Renewable residential energy systems such as rooftop solar installations can greatly improve the resilience of an at-risk region or country. This thesis pursues the following research question: what energy system would best prepare and rebuild sustainable, accessible, and reliable electricity generation after major damage from natural disasters? What value can technologies like blockchain add to building resilient, renewable, and economically viable energy systems? How might a peer-to-peer electricity trading system operate within the context of a post-hurricane society such as Puerto Rico?

This research finds that using blockchain to fortify small-scale (< 1 MW)[7] peer-to-peer renewable energy trading networks in developing urban areas tackles the problems addressed in the research question above. These technologies first improve solar energy generation by attracting homeowners to participate in this network due to improved and accessible financing. For under-developed areas, there are financing feasibilities that would eliminate any upfront cost for the renewable energy asset owner. The second improvement to energy stability comes with greater reliability of electricity generation. This is particularly important for those with no access to

[4] Yergin, Daniel. "Ensuring Energy Security." *Foreign Affairs* 85, no. 2, (2002): 69-82.
[5] Ibid.
[6] Ibid.
[7] U.S. Energy Information Administration. "More than Half of Small-scale Photovoltaic Generation Comes from Residential Rooftops." *EIA Independent Statistics and Analysis*. June 1, 2017. Accessed 2018.

electricity or with sparse and unreliable public utilities. Puerto Rico is an example of such a place and will be a focus of this research.

The structure of this thesis is as follows. The argument will first address the importance of electricity access. The relationship between energy source and environmental consequences such as air pollution is then examined as a determining factor to push for the use of solar energy. The history of hurricane impact and response in Puerto Rico is introduced and reveals the urgent necessity for a paradigm shift in the island's energy sources. Next, Puerto Rico's electricity grid is analyzed and the health co-benefits and consequences of energy source and therefore pollution exposure is analyzed. Then blockchain technology is described in depth, which leads into comparative analysis of centralized, decentralized, and distributed energy systems. Peer-to-peer energy trading reveals the value added when systems operate on blockchains, as demonstrated through examples of successful projects. After those sections, the analysis and results of research are brought forth by discussing the factors to build distributed solar networks in Puerto Rico. This thesis ends with analysis of a financial model for developing a distributed energy installation and discusses the overall impact on Puerto Rico. Methods for research include analysis of U.S. government-provided raw data and personal interviews conducted with solar developers in Puerto Rico. The analysis presented leads to the claim that building a network of distributed solar energy through residential and school rooftops in Puerto Rico is the best post-hurricane action to be taken in order to improve energy reliability, affordability, access, and resilience to future disasters and risks.

Electricity Access

Electricity is the key to improving quality of life everywhere in the world. In the international pushes to improve education, end poverty, reverse climate change, and other major sustainable goals, electricity can be the common factor. With electricity used simply as light, students can stay up past sundown to do more school work throughout the year. Light also allows people to work and build and contribute for more hours every day, thereby increasing productivity, participation in the economy, and potentially alleviating poverty. With electricity used for light, cooking, heating, and other appliances, households may not need to burn as much fuel or wood. The change in energy source from charcoal to gas-powered appliances would already reduce deforestation and fatal indoor air pollutants.[8] With access to electricity, the possibilities for economic, social, environmental, entrepreneurial, and more types of growth expand.

The United Nations (UN) Sustainable Development Goals (SDGs) outline many specific problems in the world, and Goal 7, which advocates for affordable and clean energy is one of the least publicized.[9] Around one billion people live without access to electricity. The UN SDGs recognize that 41% of the world's population in 2016 cooked with polluting fuel sources.[10] The human health considerations behind these electricity statistics are incredibly important to discuss when making decisions of community, city, and country energy use.

Energy Source and Pollutants

The scientific literature about renewable energy sources are diverse from physics, engineering, ecological, economic, and cultural perspectives. Several authors strongly claim that replacing fossil fuel sources with renewable energy will reduce carbon dioxide emissions, which will help mitigate climate change, one of the most pressing crises of our time.[11,12] Research covering how air quality may inhibit the efficiency of renewable energy like photovoltaic (PV) systems[13] reveals

---

8 Kumar, A., Kumar, K., Kaushik, N., Sharma, S., and Saroj Mishra. "Renewable energy in India: Current status and future potentials." *Renewable and Sustainable Energy Reviews* 14, (2010): 2434-2442.
9 "Goal 7: Sustainable Development Knowledge Platform." *United Nations*. Accessed January 2019.
10 Inglesi-Lotz, Roula, and Eyup Dogan. "The Role of Renewable versus Non-renewable Energy to the Level of CO2 Emissions a Panel Analysis of Sub- Saharan Africa's Big 10 Electricity Generators." *Renewable Energy* 123 (2018): 36-43.
11 Ibid.
12 "The True Cost of Fossil Fuels: Saving on the Externalities of Pollution and Climate Change." *International Renewable Energy Agency*, (2016).
13 Asl-Soleimani, E., S. Farhangi, and M.s Zabihi. "The Effect of Tilt Angle, Air Pollution on Performance of Photovoltaic Systems in Tehran." *Renewable Energy* 24, no. 3-4 (2001): 459-68.

how clean air conditions are a factor in successful energy systems. Roula et al. found specifically that increases in renewable energy use decreases CO_2 concentration in the air and the inverse to be true as well.[14] Since pollutants like NO_2, SO_2, and particulate matter are often associated the same sources as CO_2,[15,16] it follows that increased renewable energy use will also decrease those pollutants. When fossil fuels are burned less, there are fewer pollutants in the air.[17] Therefore, increasing the proportion of energy and electricity sourced from solar and wind could improve air quality, maintain energy efficiency of PV panels, and lower health consequences of pollutants.

Installing solar and switching power generation from fossil fuels to non-polluting renewable energy technology exhibits many health co-benefits for consumers and the environment. Global emissions must be addressed to mitigate the consequences of climate change. On top of that, indoor air pollution, often caused by wood or other biomass burning inside buildings for lighting or cooking significantly damage human health. Attaching the health co-benefits to discussions of solar energy usage also strengthens the advocacy for and likelihood of adoption of the technology.

Air Pollution Exposure

Public health is directly intertwined in research on energy use, distribution, and management because energy source is one of the biggest determinants of local air quality.[18] According to the World Health Organization, 4.2 million people die every year due to outdoor air pollution exposure.[19] Mortality is concentrated in highly dense urban areas and globally can be 50% higher in urban versus rural areas.[20] The consequences of air pollution disproportionately affect the regions of

---

[14] Ibid.
[15] "Sulfur Dioxide Basics." *EPA*. June 28, 2018.
[16] "Basic Information about NO2." *EPA*. September 08, 2016.
[17] Inglesi-Lotz, 2018.
[18] Dincer, Ibrahim. "Renewable Energy and Sustainable Development: A Crucial Review." *Renewable and Sustainable Energy Reviews* 4, no. 2 (2000): 157-75.
[19] World Health Organization. "Air Pollution." *World Health Organization*. February 28, 2019.
[20] Lelieveld, J., J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer. "The Contribution of Outdoor Air Pollution Sources to Premature Mortality on a Global Scale." *Nature* 525, no. 7569 (2015): 367-71.

Asia, Eastern Europe, and Africa.[21,22] Barriers to measuring air pollution related mortality – and therefore a solid understanding of the causes of this public health crisis – arise in regions that do not monitor air quality.[23] Air pollutants can stagnant or build in concentration in some areas for long period of time, posing serious hazards to health. Both indoor and outdoor air pollutants contribute to prolonged exposure and worse health impacts. Factors that contribute to these dangerous conditions include intensity of nearby combustion, topography, wind pattern and speeds, humidity, temperature, and other abiotic factors. While many of these characteristics depend on latitude and longitude, the clearest contributor to the concentration of air pollutants is energy source.[24] Around three billion people worldwide rely on biomass like coal for domestic energy use, and the trapping of emissions from indoor cookstoves leads to increased rates of cardiovascular and respiratory diseases, particularly for women who often cook for the family.[25,26] The choice of what fuel type to use to power an appliance, one home, a city, and a whole country is in fact a deliberate decision that impacts the health of the residents.

The Most Potent Pollutants

PM2.5 (particulate matter 2.5 micrometers or less in diameter), PM10 (particulate matter 10 micrometers or less in diameter), NOx (nitrogen oxides), SOx (sulfur oxides), and O_3 (ozone) are the most dangerous pollutants released from the combustion of fossil fuels. The human health effects of air pollutants are a popular topic of scientific study due to the observation of increased mortality due to pulmonary diseases. Several studies do find that these various pollutants –

---

[21] World Health Organization "Deaths attributable to ambient air pollution (age standardized, per 100 000 population)." *World Health Organization*, (2016).
[22] World Health Organization. "Ambient (outdoor) Air Quality and Health." *World Health Organization*. May 2, 2018. Accessed December 2019.
[23] Lelieveld et al., 2015.
[24] Chow, 2002.
[25] Ezzati, Majid, and Daniel M. Kammen. "The Health Impacts of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs." *Environmental Health Perspectives* 110, no. 11 (2002): 1057-068.
[26] Smith, K. R. "Indoor Air Pollution in Developing Countries: Recommendations for Research." *Indoor Air* 12, no. 3 (2002): 198-207.

particulate matter,[27] sulfur oxides,[28] ground-level ozone, carbon monoxide, and others do have negative health effects, resulting in the high mortality rates measured by the WHO. Several studies may publish contradicting results of which pollutants statistically significantly influence mortality, work days lost, or economics due to the location and time of each study.[29,30] Nevertheless, the literature and global statistics overwhelmingly tell a cautionary tale of the negative health and environmental consequences of air pollutant exposure. One question that still remains is how these pollutants may influence humans and quality of life as climate change increases global temperatures at the same time as renewable energy capacity grows internationally. The correlation between high air temperatures and mortality and hospital admissions from pollution-caused sicknesses has been validated.[31,32]

Economic Valuation of Pollution Consequences

The cost of illness and premature mortality are so severe worldwide that the health co-benefits of renewable energy are enough of an incentive to dedicate resources to cleaner and more innovative energy sources. These costs have been monetized by several economists and scientists, providing evidence that even local air pollution has a ripple effect on even the world economy. The Organization for Economic Co-Operation and Development (OECD) found that the health impact in their member countries of deaths and illnesses from air pollution exposure totaled $1.7 trillion USD in 2010.[33] The World Bank found that $225 billion was lost in labor output to the global

---

[27] Pope III, C. Arden, and Douglas W. Dockery. "Health Effects of Fine Particulate Air Pollution: Lines That Connect." *Journal of the Air & Waste Management Association* 56, no. 6 (2006): 707-08.
[28] Zuidema, Thijs, and Andries Nentjes. "Health Damage of Air Pollution: An Estimate of a Dose-response Relationship for The Netherlands." *Air Pollution in the 21st Century - Priority Issues and Policy Studies in Environmental Science*, (1998): 981-1006.
[29] Chow, Judith C., and John G. Watson. "Review of PM2.5 and PM10 Apportionment for Fossil Fuel Combustion and Other Sources by the Chemical Mass Balance Receptor Model." *Energy & Fuels* 16, no. 2 (2002): 222-60.
[30] Zuidema et al., 1998.
[31] Katsouyanni, K., A. Pantazopoulou, G. Touloumi, I. Tselepidaki, K. Moustris, D. Asimakopoulos, G. Poulopoulou, and D. Trichopoulos. "Evidence for Interaction between Air Pollution and High Temperature in the Causation of Excess Mortality." *Archives of Environmental Health: An International Journal* 48, no. 4 (1993): 235-42.
[32] Koken, Petra J M, Warren T. Piver, Frank Ye, Anne Elixhauser, Lola M. Olsen, and Christopher J. Portier. "Temperature, Air Pollution, and Hospitalization for Cardiovascular Diseases among Elderly People in Denver." *Environmental Health Perspectives* 111, no. 10 (2003): 1312-317.
[33] OECD. "The Cost of Air Pollution - Health Impacts of Road Transport." *OECD*. May 21, 2014. Accessed November, 2018.

economy in 2010 alone from premature deaths, which doesn't include labor hours lost to illness.[34] Labor loss amounts take up around one percent of regions' entire GDPs due to premature deaths – 0.83% in South Asia, 0.25% in East Asia and the Pacific, 0.61% in Sub-Saharan Africa.[35] Though less than one percent may seem small, these are significant percentages that tell a particularly dire story of the setbacks facing developing regions. For places with aging populations like East Asia and with younger population demographics like Sub-Saharan Africa, the "earning potential of younger populations" [36] is not to be underestimated, since a smaller percentage of the population is earning income. The metric of Disability-Adjusted Life Years incorporates the weight that age of death carries in a community by summing the "Years of Life Lost due to premature mortality … and the Years Lost due to Disability for people living with the health condition or its consequences."[37] Hansen and colleagues found strong links in the data between particulate matter concentration and sick-leave,[38] which are present in the atmosphere mostly due to fossil fuel combustion.[39] Increased sick leave caused by air pollution translates to reduced labor productivity, reduced income, and stunted economic growth. Expanding past only income potential, the aggregate costs of welfare losses equaled $5 trillion worldwide in 2013.[40] At this extremely high cost, it becomes financially preferable to change policies and improve energy systems.

Health Care Costs of Pollution

Lawmakers may not respond to global aggregate losses and valuations of intangible variables, so the statistics on healthcare expenditures from air pollution due to fossil fuel combustion make the final case that air pollution is an extremely dangerous and tangible threat to human health and

[34] Ibid.
[35] Ibid.
[36] World Bank. "Air Pollution Deaths Cost Global Economy US$225 Billion." 2016.
[37] "Metrics: Disability-Adjusted Life Year (DALY)." *World Health Organization*. March 11, 2014. Accessed April 09, 2019.
[38] Hansen, Annet C., and Harald K. Selte. "Air Pollution and Sick-leaves – is there a Connection? A Case Study using Air Pollution Data from Oslo." *Statistics Norway, Research Department* 197, (1997).
[39] Chow, 2002.
[40] World Bank. "Air Pollution Deaths Cost Global Economy US$225 Billion." 2016.

government expenditure. Extensive literature is published on the provenance of health expenditures, including population demographics like ageing,[41,42] income,[43] foreign aid received per capita,[44] and number of practicing physicians.[45] Recently, the literature analyzing driving forces of health care expenditure expanded to incorporate the role of environmental quality.[46,47] These significant losses do create ripples in local and international markets and certainly place a large cost burden on healthcare systems.

Narayan and colleagues found that in OECD countries, air pollutant concentrations do increase expenditure: 1% in carbon monoxide emissions creates a 0.42% increase in health expenditures and a 1% increase in sulphur oxide emissions creates a 0.04% increase.[48] More research is necessary to link particulate matter emissions with percent change of national healthcare expenditure, however the economic and health consequences of high PM concentrations are well-proven.[49] Purposeful investments in public health and environmental protection like air quality create reduced health care expenditures,[50] a key co-benefit of investment in renewable energy. The majority of literature published on environmental quality's influence on health care expenditures are conducted in the United States and Canada, and so more research on these particular correlations should be conducted. Nevertheless, the findings in the current literature can translate to developing regions given global and regional statistics of mortality and pollution. Many countries are projected

[41] Di Matteo, Livio, and Di Matteo, Rosanna. "Evidence on the determinants of Canadian provincial government health expenditures: 1965–1991." *Journal of Health Economics* 17, no. 2 (1998):211-228.
[42] Murthy, N. R. Vasudeva, and Victor Ukpolo. "Aggregate Health Care Expenditure in the United States: Evidence from Cointegration Tests." *Applied Economics* 26, no. 8 (1994): 797-802.
[43] Hansen, Paul, and Alan King. "The Determinants of Health Care Expenditure: A Cointegration Approach." *Journal of Health Economics* 15, no. 1 (1996): 127-37.
[44] Gbesemete, Kwame P., and Ulf-G. Gerdtham. "Determinants of Health Care Expenditure in Africa: A Cross-sectional Study." *World Development* 20, no. 2 (1992): 303-08.
[45] Murthy et al., 1994.
[46] Jerrett, M. "Environmental Influences on Healthcare Expenditures: An Exploratory Analysis from Ontario, Canada." *Journal of Epidemiology & Community Health* 57, no. 5 (2003): 334-38.
[47] Narayan, Paresh Kumar, and Seema Narayan. "Does Environmental Quality Influence Health Expenditures? Empirical Evidence from a Panel of Selected OECD Countries." *Ecological Economics* 65, no. 2 (2008): 367-74.
[48] Ibid.
[49] Zhang, Minsi, Yu Song, Xuhui Cai, and Jun Zhou. "Economic Assessment of the Health Effects Related to Particulate Matter Pollution in 111 Chinese Cities by Using Economic Burden of Disease Analysis." *Journal of Environmental Management* 88, no. 4 (2008): 947-54.
[50] Jerrett, 2003.

to increase the stake of renewable energy in their national energy mixes.[51,52,53,54] Developing ways technology and innovation can help achieve these energy goals will greatly aid climate change mitigation as well help prevent air pollution exposure related mortality, economic downturn, and diminished quality of life.

Different Categories within Renewable Energy

In order to fully capture the health co-benefits of increasing renewable energy use, the difference between polluting and non-polluting renewable energy is important to define. There are several sources of energy such as biofuels and wood that are renewable, as the sources may be regrown in a time scale that would replenish what is consumed. However, both these renewable sources are burned at consumption, and the process of combustion emits many of the air pollutants that contribute to the mass health effects discussed above. Some countries will pride themselves on increasing levels of renewable energy by increasing biofuel use, yet this is a dangerous false celebration of environmental improvement.[55] The European Court of Justice even filed a lawsuit on March 4, 2019 arguing that wood pellets and forest biomass should not be considered as renewable energy.[56,57] Instead, renewable energy sources such as solar, wind, geothermal, and tidal are both renewable and do not emit at the time of consumption or use, and should therefore be the focus of growth in roadmaps to sourcing more sustainable and clean energy. There are negative externalities associated with the mining of metals, manufacturing, and transportation of these renewable energy technologies that render natural resources like solar radiation and wave movement capturable. The

---

[51] "Renewables Global Status Report." *REN21*. 2018.
[52] "The Paris Agreement Summary." *Climate Focus*. December 28, 2015.
[53] "The True Cost of Fossil Fuels: Saving on the Externalities of Pollution and Climate Change." 2016.
[54] Martinot, E., Chaurey. A., Lew, D., Moreira, J.R., Wamukonya, N. "Renewable Energy Markets in Developing Countries." *Annual Review of Energy and the Environment* 27, {2002}: 309-348.
[55] "The True Cost of Fossil Fuels: Saving on the Externalities of Pollution and Climate Change." 2016.
[56] Sengupta, Somini, and Charlotte De La Fuente. "Copenhagen Wants to Show How Cities Can Fight Climate Change." *The New York Times*. March 25, 2019. Accessed March 2019.
[57] "Lawsuit Filed before European Court of Justice against Inclusion of Forest Biomass in Renewable Energy Directive II." *Bernard Energy*. March 4, 2019. Accessed March 2019.

materials and technology do cause pollution if those processes and manufacturing industries are run on fossil fuels. However, they do not pollute continuously throughout consumption, which is a large differentiator. The UN SDGs choose to make this distinction through the word "modern,"[58] though still includes "bioenergy" in this definition, which could leave room for interpretation to developers. Given the incredible health consequences of fossil fuels, this thesis will continue to address non-source-polluting renewable energy sources as “renewable energy sources” for simplicity.

Conclusion for Electricity & Public Health

From these literature reviews of air pollutants, fuel sources, health consequences, and renewable energy, it becomes clear there are gaps in research. Despite these gaps, a prevailing message emerges that renewable energy could largely transform the environments humans live in for the better. There still remain political and financial barriers to realizing the full potential of renewables. Increasing the percentage of clean energy used on a national level could also increase an area's energy resilience in the face of natural disasters, oil embargoes, price or trade agreement fluctuations, or other events that can put a nation's energy supply in jeopardy. Utilizing the tools of science and technology to improve on both large- and small-scale renewable energy sources can increase the public support and propel the development of these sources for a more sustainable planet.

Puerto Rico Hurricane Background

Climate & Hurricane History

Security of energy sources is one of the most important considerations to build a resilient and successful nation. In 2014, Secretary of State of the United States John Kerry announced a task

[58] "Goal 7: Sustainable Development Knowledge Platform." *United Nations*. Accessed January 2019.

force to integrate climate change and national security analysis in foreign policy.[59] At the heart of this is risk. Governments want to minimize risk to their national interests. The biggest factors to put physical infrastructure at risk when it comes to climate change are extreme whether events. The top five most costly hurricanes to the U.S. all occurred since 2012 and total around $500 billion in damages, according to the National Oceanic and Atmospheric Administration (NOAA).[60] Hurricanes are particularly threatening to energy systems, as the combination of wind and rain can significantly halt electricity generation of power plants and destroy transmission lines among other damages.

2017 brought the fragility of Puerto Rico's energy management to the forefront of news, enlightening the need for a system update. As three of the historically hardest-hitting hurricanes swept through and destroyed the Caribbean, Puerto Rico, Texas, other areas within 10 days of each other, unforeseen damages and systemic problems emerged. Hurricanes Harvey, Irma, and Maria's estimated damages totaled $125, $50, and $90 billion respectively.[61,62] Following Category 4 storm Harvey with consecutive Category 5 storms Irma and Maria, the timeline of these hurricanes was extraordinarily devastating.

The two most devastated U.S. locations from the consecutive hurricanes were Houston and Puerto Rico. While both Harvey and Maria were hurricanes on the high end of the Saffir-Simpson scale, Harvey raged more heavily with rain and flooding while Maria with torrential winds.[63] There is plentiful research and opinion on the failures of policy, hydrological planning, insurance requirements, communication services linked to power availability, presidential indifference, and

---

[59] Reuters. "Kerry: Panel to Integrate Climate Threats into Foreign Policy Plans." *Business Insider*. November 10, 2015. Accessed March 2019.
[60] Office for Coastal Management. "Hurricane Costs." *National Oceanic and Atmospheric Administration*. Accessed March 2019.
[61] Office for Coastal Management. "Hurricane Costs." 2019.
[62] Fritz, Angela. "Everything You Need to Know about Hurricane Irma." *The Washington Post*. September 20, 2017. Accessed 2019.
[63] Gonzalez, Robbie. "The Monumental Task of Restoring Houston After Harvey." *Wired*. September 07, 2017. Accessed March 2019.

health care.[64,65,66,67,68] All of these compounding problems left both Houston and Puerto Rico with extremely long and painful recovery times. The four days of rain dumped on Houston flooded the city way beyond designated flood zones damaging 203,000 homes, sending 39,000 people into shelters, cutting off power for 250,000 people,[69] requiring Federal forces to rescue 122,331 people in Texas,[70] and creating a death toll of 75-82 people 45 days after landfall.[71] Hurricane Harvey was larger in scale when measuring the number of people and amount of property impacted in Houston, but Puerto Rico had a harder road to recovering due to their economic history and location. In Puerto Rico, over 100,000 homes were demolished,[72] 200,000 refugees huddled in government and American Red Cross shelters,[73] hospitals treated 33,164 patients in the first 45 days,[74] the entire island lost power in the first day and only recovered 41% of power after 45 days,[75] and 1,052 were dead by day 42 after the landfall.[76] The death toll was a politicized and inaccurate measurement of damage all through the fall of 2017, each source providing a different number. The official death toll in Puerto Rico still rests at 2,975 when separate analysis records 4,645 deaths from September to December 2017.[77,78] The cost for reconstruction and loss in economic productivity – not including the environmental decimation of their banana crops, coffee plants, and livestock – in Puerto Rico after Hurricane Maria is estimated between $30 – 85 billion.[79]

---

[64] Federal Emergency Management Agency. "Statistics Progress in Puerto Rico Hurricane Maria Update*." U.S. Department of Homeland Security*. November 6, 2017. Accessed 2017.
[65] Fessenden, Ford, Robert Gebeloff, Mary Williams Walsh, and Troy Griggs. "Water Damage From Hurricane Harvey Extended Far Beyond Flood Zones." *The New York Times*. September 02, 2017. Accessed March 2019.
[66] Soto, Darren. "Report on Federal Response to Hurricane Maria in Puerto Rico." *U.S. House of Representatives*. October 2, 2017.
[67] Kishore, Nishant and Marqués, Domingo and Mahmud, Ayesha and Kiang, Mathew V. and Rodriguez, Irmary and Fuller, Arlan and Ebner, Peggy and Sorensen, Cecilia and Racy, Fabio and Lemery, Jay and Maas, Leslie and Leaning, Jennifer and Irizarry, Rafael A. and Balsari, Satchit and Buckee, Caroline O. "Mortality in Puerto Rico after Hurricane Maria." *New England Journal of Medicine*. (2018): 379(1): 162-170.
[68] Farber, Daniel A. "Response and Recovery after Maria: Lessons for Disaster Law and Policy." *UC Berkeley*, June 19, 2018.
[69] Amadeo, Kimberly. "Hurricane Harvey Shows How Climate Change Can Impact the Economy." *The Balance*. Accessed December 14, 2017.
[70] Federal Emergency Management Agency. "Historic Disaster Response to Hurricane Harvey in Texas." *U.S. House of Representatives*. September 22, 2017. Accessed 2018.
[71] George, Cindy, Margaret Kadifa, Lindsay Ellis, and Keri Blakinger. "Storm Deaths: Harvey Claims Lives of More than 75 in Texas." *Houston Chronicle*. October 09, 2017. Accessed 2018.
[72] Soto, 2017.
[73] Cordoba, Jose De. "Puerto Rico Tallies Up Devastation From Hurricane Maria." *The Wall Street Journal*. September 24, 2017. Accessed 2018.
[74] Federal Emergency Management Agency. "Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria." *U.S. Department of Homeland Security*. October 31, 2017. Accessed 2018.
[75] FEMA. "Statistics Progress in Puerto Rico Hurricane Maria Update*."* 2017.
[76] Robles, Frances, Kenan Davis, Sheri Fink, and Sarah Almukhtar. "Official Toll in Puerto Rico: 64. Actual Deaths May Be 1,052." *The New York Times*. December 08, 2017. Accessed December 12, 2017.
[77] Fink, Sheri. "Nearly A Year After Hurricane Maria, Puerto Rico Revises Death Toll to 2,975." *The New York Times*. 28 August, 2018.
[78] Kishore et al., 2018.
[79] "Hurricane Maria Is a Nightmare for Puerto Rico's Economy." *CNN Money*. September 25, 2017. Accessed October 2017.

Given Puerto Rico's recent economic crisis and bankruptcy, paying for that reconstruction is difficult given that the damage could reflect 30-82% of Puerto Rico's $103 billion economy in 2017.[80] This is an incredibly wide range, yet even the lower end is a large setback. The location of hurricanes is extremely important as it relates to recovery because "one of the guiding concepts of disaster relief in years is that neighbors are the real first responders."[81] Being an island whose neighbors were also suffering wreckages, Puerto Rico did not receive the volunteer, government, and financial response that Houston found in their neighbors on the mainland of the United States.

Puerto Rico, a territory of the United States, may not have voting rights in Congress, but the U.S. government still has the same responsibility to the U.S. citizens of Puerto Rico as it does to any U.S. state.[82] Puerto Ricans have been U.S. citizens since the Jones Act passed exactly 100 years prior to the horrific hurricane season of 2017.[83] As far as receiving resources from the Federal Emergency Management Agency (FEMA), who's primary purpose under the U.S. Department of Homeland Security is to coordinate disaster response, Puerto Rico is entitled to equitable treatment.

The factor that most prolonged suffering was the lack of power in Puerto Rico. ATMs, credit cards, and Nutrition Assistance Program Cards were all rendered useless in the power outage, so few people had access to immediate funds or help.[84] FEMA does its best to ensure the chronology of bureaucratic processes is not delayed, but "this situation was exacerbated by the fact that the government of Puerto Rico lacks an ability to effectively communicate between officials and agencies or assess damage due to virtually no internet or cell phone service," reported Congressman Daren Soto of Florida.[85] The failure of communication systems was detrimental to Puerto Rico's fate since all modern systems including Federal Government response, rescue, and transport all rely on

[80] "Hurricane Maria Is a Nightmare for Puerto Rico's Economy." 2017.
[81] Graham, David A. "Is the Federal Government Doing Enough for Puerto Rico?" *The Atlantic*. September 26, 2017. Accessed March 2019.
[82] Webber, Tim. "What Does Being A U.S. Territory Mean For Puerto Rico?" *NPR*. October 13, 2017. Accessed March 2019.
[83] Ibid.
[84] Soto, 2017.
[85] Soto, 2017.

coordination and virtual contact to run efficiently. The reality is that power access only restore by 21% after 30 days, 41% after 45 days, 84% after five months, 99% after a full six months, and finally reaching 100% 18 months after Hurricane Maria's landfall on September 20th.[86,87,88] Aging infrastructure, mismanagement, and reliance on fossil fuels prevented the island from fully regained pre-hurricane capacity in Puerto Rico.[89,90,91] The large majority of Houston residents who did lose power had the ability to call for help, request emergency grants, and claim flood insurance all within the first 24 hours of disaster.[92] Hurricanes and other storms like are likely to become more frequent and powerful in the Atlantic, given the trends and research surrounding sea surface temperatures and hurricane activity.[93] A system update to the energy sector on the island is not only critical to assist with faster recovery from storms in the future, but also can transition Puerto Rico away from a history and present existence of an extremely unreliable government-run grid.

Medical Help After Hurricanes

The true magnitude of the hurricanes and urgent importance of updating Puerto Rico's energy system can better be understood by considering the complete absence of resources on the island post-hurricanes. The absence of power was an immense problem that inhibited medical assistance, the availability of fresh water, and food. Hurricanes cause a multitude of human health problems, and moving people out of physical harm is a first priority. Bacterial infection, pollution exposure, and diseases are then crucial to minimize through operating hospitals and flying in supplies and generators through airports. The Department of Health and Human Services activated

---

[86] FEMA. "Statistics Progress in Puerto Rico Hurricane Maria Update." 2017.
[87] Lu, Denise, and Chris Alcantara. "Analysis | After Hurricane Maria, Puerto Rico Was in the Dark for 181 Days, 6 Hours and 45 Minutes." *The Washington Post*. April 4, 2018. Accessed February 2019.
[88] "Puerto Rico Power Fully Restored 18 Months After Hurricane Maria Wiped Out the Grid." *The Weather Channel*. March 21, 2019. Accessed March 2019.
[89] FEMA. "Statistics Progress in Puerto Rico Hurricane Maria Update." 2017.
[90] Soto, 2017.
[91] Lu et al., 2018.
[92] Amadeo, 2017.
[93] Geophysical Fluid Dynamics Laboratory. "Global Warming and Hurricanes." *National Oceanic and Atmospheric Administration*. Accessed April 2019.

the "National Disaster Medical System Definitive Care Reimbursement Program, which reimburses medical facilities and hospitals for the medical care costs of patients medically evacuated following disasters," which is an important step to save lives.[94] However in Puerto Rico, 56 of the 68 hospitals were only partially operational nine days after the hurricane hit,[95] and one doctor recommended that sick patients leave the island to seek medical treatment,[96] which is not an option for those without the financial means. The Department of Agriculture arrived a week after Hurricane Maria's landfall in Puerto Rico with chainsaw teams to clear roads, so FEMA medical and other supply drops didn't reach the hardest hit communities until after transportation access improved, and vessels carrying supplies often had to wait for ports to open or lift restrictions.[97]

Water Sanitation and Sewage Post-Maria

The Environmental Protection Agency sampled and disinfected water sources in the aftermath of both Hurricane Harvey and Maria, though Puerto Rico's water infrastructure was in a worse condition. Potable water was not readily available, and took over a month to restore 83% of access on the island.[98] The EPA determined on October 11th, 2017 that Puerto Rico's wastewater infrastructure was not functioning due to the blackout of power.[99] They reported that "raw sewage released into waterways, including coastal waters, streams, rivers, will continue in some areas until repairs can be made and/or power is restored,"[100] not only showing the failure of public infrastructure and necessity for more resilient power networks, but also heightening health risks on the island. The degradation of environmental quality on Puerto Rico through the pollution of waters and the destruction of trees and habitat will make the recovery of clean water and living conditions

---

[94] "Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria." *FEMA*, 2017.
[95] Ibid.
[96] Graham, 2017.
[97] "Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria." *FEMA*, 2017.
[98] FEMA. "Statistics Progress in Puerto Rico Hurricane Maria Update*."* 2017.
[99] "Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria." *FEMA*, 2017.
[100] Ibid.

all the more difficult even after the island recovers to pre-hurricane states. The differential emergency response to Puerto Rico's needs from the U.S. government[101] made clear the necessity for the island to become self-reliant as soon as possible, particularly in their sourcing of electricity.

Hurricane Irene in 2011: Fragility is Not An Isolated Event

The necessity for innovation for Puerto Rico's energy system is even more prominent when analyzing how hurricanes other than Harvey and Maria affected the island. When energy was completely cut off for over half of the population for over two months, the unspoken message was sent to residents that fixing the fundamental problems in the energy network was not be a priority of either the U.S. or the Puerto Rican government. The literature shows a strong association between remoteness and length of time without necessities like electricity, water, and cellular coverage.[102] This represents the instability caused by a grid-dominated system. While 2017 is clear in the memories of Puerto Rican residents, Maximo Torres, a solar developer and founder of Maximo Solar in Puerto Rico, recalls a similar catastrophe merely six years earlier. Hurricane Irene demolished Puerto Rico on its way to Florida.[103] For Mr. Torres's solar company, both these hits of Hurricane Irene were particularly devastating. When residents experience both frequent and short-term black- and brownouts of the electricity grid as well as more dramatic and long-term outages, their preference of energy resources shifts. Mr. Torres reported that his company experience an increase in sales for solar services and products in Puerto Rico. Maximo Solar regained its own power within 24 hours of Hurricane Maria in 2017 and was ready to get out on the ground and help set up systems to provide electricity to those who had lost everything. The company had a similar rapid recovery story after Hurricane Irene in 2011. What made Hurricane Irene a bigger setback for Maximo Solar compared

[101] Farber, 2018.
[102] Kishore et al., 2018.
[103] "Hurricane Irene Slams Puerto Rico, Eyes U.S." *CBS News*. August 25, 2011. Accessed March 2019.

to Hurricane Maria was the effect on Florida, where Mr. Torres's company received all their stock of solar panels, inverters, batteries, and other equipment. Shipments were no longer processed due to the damage in Florida, and so energy companies reliant on mainland manufacturing were unable to help serve the people in Puerto Rico who lost power.[104]

Building resilient power networks should be a priority moving forward for Puerto Rico, and evidence demonstrations that it is possible to withstand Category 5 hurricanes and recover power quickly. Interviews with Puerto Rico residents and solar developers confirmed that "Most homes that had solar panels installed on their roofs still have both the roof and the panels [after Hurricane Maria]. Some of the panels may have been damaged by flying debris, but the majority of the roof mounted solar systems were spare."[105] The history of hurricane damage and the likelihood for future storms in Puerto indicate that the best step forward for recovery and prosperity is a revamp of the energy system. Solar technologies and distributed energy networks may provide the best option to provide the reliability, remote and urban access, and affordability in Puerto Rico given the contextual, anecdotal, statistical, and financial research and analysis presented in this thesis.

Unreliable Grid: Why is Puerto Rico's Energy System So Unreliable?

The Puerto Rico Electric Power Authority (PREPA) – Autoridad De Energía Eléctrica in Spanish – is largely the cause of the island's energy infrastructure instability, and the most appropriate solutions work through creating complementary systems exterior of PREPA's control. PREPA is a government-owned corporation responsible for electricity generation, distribution, and power transmission.[106] Serving 1.5 million clients, and rounding the average household size to about two people per household, PREPA serves just about all of the 3.3 million people in Puerto Rico.[107]

[104] Ibid.
[105] "Battery Backup for Puerto Rico's Grid Tied Solar Power Systems." *Solar Power News & DIY Solar Tips*. April 06, 2018. Accessed March 2019.
[106] Autoridad De Energía Eléctrica (PREPA)."Sistema Eléctrico: Quienes Somos Sistema Eléctrico." *Autoridad De Energía Eléctrica*. 2019. Accessed February 2019.
[107] Ibid.

Operating four main power stations, Costa Sur, Complejo Aguirre, San Juan, and Palo Seco, PREPA generates 69% of energy from oil.[108] PREPA has historically been notorious for inefficiency and unreliability while it created immense financial burden for the Puerto Rican government.[109] Of Puerto Rico's current $74 billion in debt, the Rocky Mountain Institute (RMI), an environmental non-governmental organization (NGO), estimates PREPA is responsible for $8 billion of the total.[110] Even the PREPA board President Jose Carrion himself publicly affirmed the conclusion that, particularly today, Puerto Rico needs new innovation and a completely rethought energy ecosystem.[111] Carrion disclosed that the power company has been abused by corruption and bankrupted by administrators. He said that "of all the realities [Hurricanes] Irma and Maria confronted us with, without a doubt the most evident is that Puerto Rico's energy system does not work."[112] RMI argues that PREPA must be removed to clear the path for an independent regulator to oversee the utilities, which would foster more investor trust and bring more projects to Puerto Rico.[113]

Distributed solar networks provide a tantalizing opportunity to avoid the corruption and debt that plague Puerto Rico's current energy infrastructure and management. Private ownership and independence from the grid are essential to provide Puerto Rico with greater energy resilience and reliability. A shift towards distributed solar requires the involvement of private sector developers and other businesses, a move Carrion supports: In February 2018 he forecasted that even after power is fully restored to Puerto Rico, privatization of electricity is needed.[114]

---

[108] Ibid.
[109] O'Malley, Martin. "Resilient Rebuilding in Puerto Rico." *Rocky Mountain Institute*. May 30, 2018. Accessed March 2019.
[110] O'Malley, 2018.
[111] Jervis, Rick. "'5 Months without Power': Blackout Is Latest Snag in Puerto Rico's Long Recovery from Hurricane Maria." *USA Today*. February 13, 2018. Accessed 2019.
[112] Ibid.
[113] Torres Placa, Tomás J., Roy Torbert, and Mike Henchen. "Collaborating for Puerto Rico's Energy Transformation." *Rocky Mountain Institute*. October 11, 2018. Accessed 2019.
[114] Ibid.

Necessary Elements of a New Energy System

In the aftermath of such tragedy lies an opportunity and willingness to create a cleaner, more independent, and economically stable energy system. The difficulties of transitioning energy sources in poor and underdeveloped regions should not be underestimated, however. The destruction from the hurricanes did not leave a completely blank canvas on which to reinvent the power generation system, as some energy developers may romanticize. Emergency and unstable connections were set up rapidly after the hurricanes.[115] Now that all those previously served by PREPA all have power access back, the deeper repairs and rebuilding that even PREPA's transmission and distribution director, Jose Sepulveda, acknowledged are necessary, can commence.[116] The price of electricity in Puerto Rico is among the highest in all of the U.S., fluctuating around 22.77 cents per residential kilo-watt hour (kWh), compared to the residential national average 12.47 cents per kWh.[117] Placing the power and control of generation into the hands of individuals and communities could not only create diversity in energy source thereby increasing resilience in emergency circumstances, but also could be less expensive for consumers and businesses.

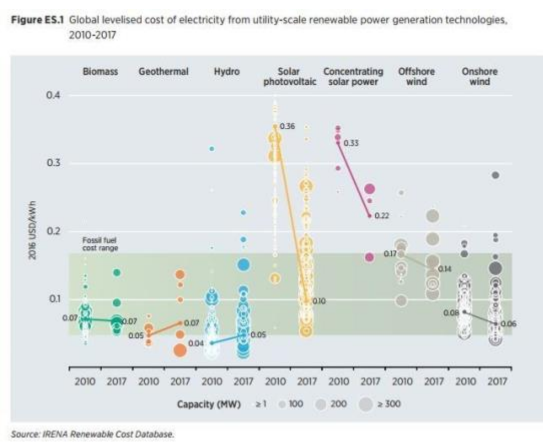
Of all the renewable energy options, solar energy is the most malleable with which to test new systems and emerging technologies, like blockchain. Prices per kWh for solar are plummeting as depicted in Figure A,[118] trillions of dollars are funding megawatt (MW) and gigawatt (GW) solar power plant projects across the globe, and a cultural acceptance of solar PV technology worldwide is expanding. Solar electricity generation is a versatile technology well suited to serve many regions, including Puerto Rico, in several ways. The first reason is the diversity in scale. Solar is a modular system and functions equally well on a small or a multi-megawatt scale. Adding more panels and

---

[115] "Puerto Rico Power Fully Restored 18 Months After Hurricane Maria Wiped Out the Grid." *The Weather Channel*. March 21, 2019. Accessed March 2019.
[116] Ibid.
[117] U.S. Energy Information Administration. "Puerto Rico: Territory Energy Profile Data." *EIA Independent Statistics and Analysis*. March 21, 2019. Accessed March 2019.
[118] Spaen, Brian. "In 2 Years, Renewables Will Be Cheaper than Fossil Fuels." *World Economic Forum*. January 17, 2018. Accessed March 2019.

building up capacity is not difficult and all scales have already been built and tested across the world. Photovoltaic panels can be retrofitted onto houses or community centers or they may remotely supply electricity to an entire city.[119] Solar is also one of the most developed renewable energy sources. Prices in solar panels themselves, not just the electricity they generate, have significantly decreased over the years and the improvements of energy efficiency have been well-tracked.[120,121] A third reason is that solar power is consistent in timing. While the sun does not shine at night, average hours of sunlight are predictable and reliable. Solar power is also at the heart of innovation, with several startups and companies already running test cases on microgrids, community-owned solar, and innovative finance models for renewable energy with solar in areas with unreliable grid structures.[122] The comfort with solar allows for innovation, and the potential of an emerging technology like blockchain to add value to solar PV systems should be explored.

Figure A: Global levelized cost of electricity from utility-scale renewable power generation technologies



Spaen, Brian. "In 2 Years, Renewables Will Be Cheaper than Fossil Fuels." World Economic Forum. January 17, 2018. Accessed March 2019. https://www.weforum.org/agenda/2018/01/renewables-will-be-equal-or-cheaper-than-fossil-fuels-by-2020-according-to-research.

Blockchain Technology Background

Blockchain technology functions as a digital record book. Also called distributed ledger technology (DLT), blockchain records transactions between parties in an immutable and verified

[119] Nogot, Fatiha. Interview by Pascale Bronder. Personal Interview. December 31, 2019.
[120] Fares, Robert. "The Price of Solar Is Declining to Unprecedented Lows." *Scientific American*. August 27, 2016. Accessed February 2019.
[121] Matasci, Sara. "Solar Panel Cost: Avg. Solar Panel Prices by State in 2019 | EnergySage." *Solar News*. 2019. Accessed February 2019.
[122] Bronder, Pascale. "Effective Disruption: How Blockchain Technology Can Transform the Energy Sector." *LinkedIn*. August 11, 2017.

way. Instead of a centralized system with one party controlling the majority of the information, blockchain operates across several equal nodes – counterparties or computers that can be personal, corporate, or government – in a distributed network, as visually represented in Figure B. Simply explained in six sentences:

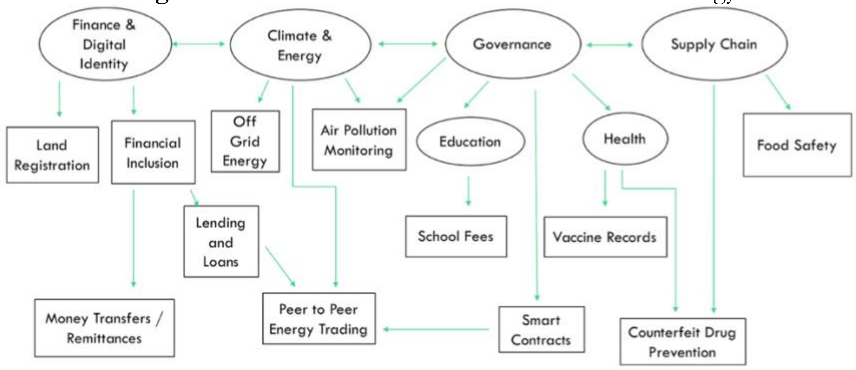
> "transactions are time-stamped into a block, and a series of those blocks creates a chain. Every time a new block is added or verified, it is updated in real time on the networks of everyone participating on the blockchain. To form and verify a block, every member involved in a transaction must actively agree that the transaction occurred. This consensus of members makes a blockchain immutable. Every new block is built on top of the cryptographic computer coding of all the preceding blocks. Therefore, the only way to change or alter a transaction is by creating a new transaction that all the constituents agree to."[123]

The contents of the transactions, or blocks, can be virtually anything: money, medical records, a bag of coffee beans, land ownership titles, kilowatt hours (kWh) of electricity, and more. Through this system, everyone on that blockchain can track each transfer-of-hands and receive extremely transparent confirmation about what is being traded, when, and who is involved.[124] The process of verification with blockchain generates the value of trust that is one of the most recognizable qualities of blockchain technology. Distributed networks allow direct transactions, often eliminating middlemen and third parties. The high level of accountability embedded into the functioning of these DLTs predisposes that those participating don't actually need to trust the other entities involved – be it an individual, bank, organization, etc. – due to the consensus required to complete any transaction.

[123] Bronder, 2017.
[124] Bronder, 2017.

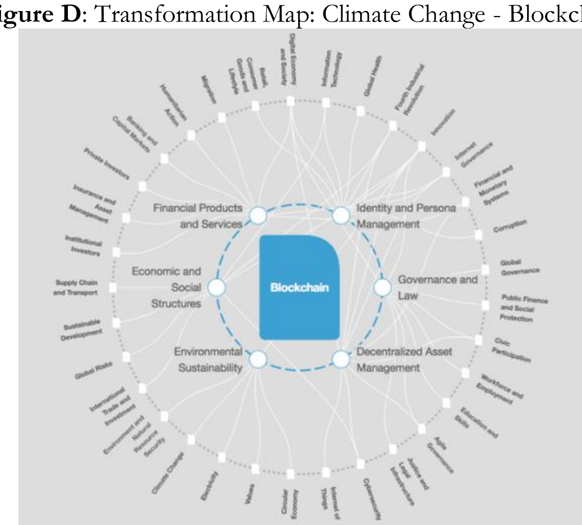
How the Trading Works: Smart Contracts, Solar Panels, and Transmission Lines

Figure C: Potential Use-Cases for Blockchain Technology



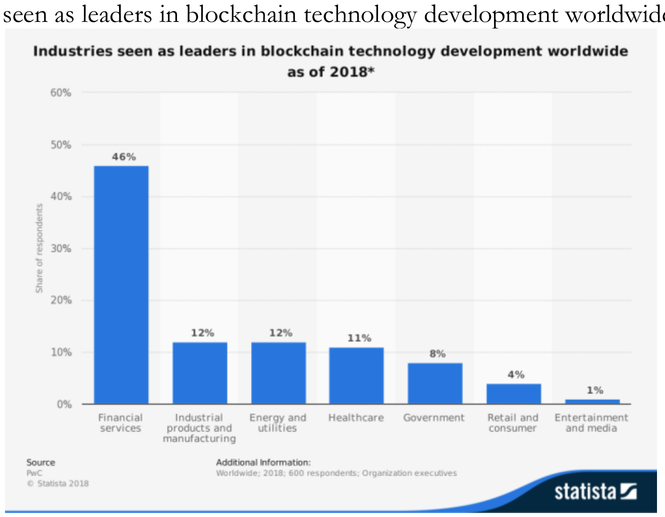
Created to visualize the landscape of applicable fields for blockchain. These examples could be categorized as "blockchain for good," meaning these uses focus on using the administrative advantages of blockchain technology to help disenfranchised people. There is an element of social responsibility in this non-exhaustive diagram.

Figure D: Transformation Map: Climate Change - Blockchain



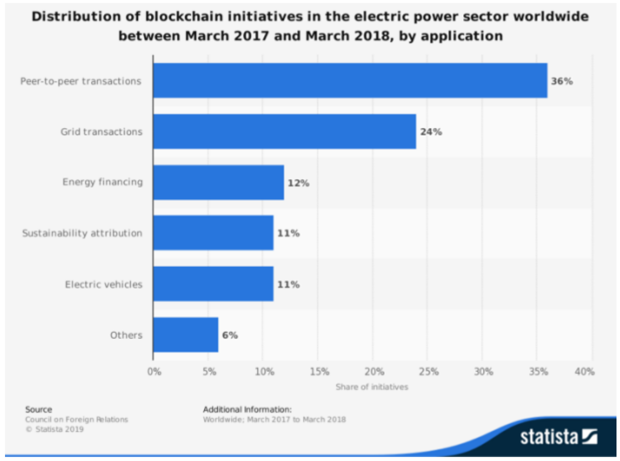
Yale University, and Expert Network. "Transformation Maps: Climate Change." World Economic Forum. Accessed January 2019. https://toplink.weforum.org/knowledge/insight/a1Gb0000000LHVfEAO/explore/summary.

Figure E: Industries seen as leaders in blockchain technology development worldwide as of 2018 - Statista



PwC. "Industries seen as leaders in blockchain technology development worldwide as of 2018." *Statista – The Statistics Portal.* Retrieved March 22, 2019, from https://www.statista.com/statistics/920747/worldwide-blockchain-technology-development-leading-industries/.

Figure F: Peer-to-Peer Transactions Are Most-Used Blockchain Application in Energy Sector



Council on Foreign Relations. "Distribution of blockchain initiatives in the electric power sector worldwide between March 2017 and March 2018, by application." *Statista - The Statistics Portal.* Retrieved March 8, 2019, from https://www.statista.com/statistics/866609/electricity-blockchain-initiatives-globally-by-application/.

The key to using any new technology is finding which fields the technology will truly add value to. Blockchain technology is not a silver bullet solution by any means. The best uses for blockchain have been studied, and key sectors that highlight more altruistic uses than the typical currency-driven uses include financial and digital identities, supply chain provenance, air pollution monitoring, and energy sharing.[125] Figure C depicts a simplified landscape of blockchain use cases. The World Economic Forum (WEF) verifies the connections among blockchain, global health, public finance and social protection, workforce and employment, circular economy, electricity, environment and natural resource security, and sustainable development in their Transformation Map on Climate Change seen in Figure D.[126,127] WEF supports the notion that improved and appropriate technology can benefit the environment.[128] Embracing the new wave of technology can help environmental monitoring, regulation, and scientific improvement in fields of agriculture, forestry, pollution, and more in ways that may not yet be developed. Statistics and polls reveal that the second-best industry for the application of blockchain is in the field of energy and utilities [Figure E]. Within energy, peer to peer energy transactions are the most common use for blockchain

[125] Bronder, 2017.
[126] Landale, James. "What Is a Transformation Map?" *World Economic Forum*. November 8, 2017. Accessed December 2018.
[127] Yale University, and Expert Network. "Transformation Maps: Climate Change." *World Economic Forum*. Accessed January 2019.
[128] "Transformation Maps: Environment and Natural Resource Security." *World Economic Forum*. Accessed January 2019.

[Figure F]. In this type of energy system, all agents are "prosumers" – both producers and consumers of their own and others' electricity. Building distributed energy systems on blockchain will enable cleaner and more reliable, affordable, resilient, and efficient renewable energy systems.

Blockchains operate at their characteristically reliable and efficient levels through the use of smart contracts. Smart contracts are digital facilitators and enforcers for transactions. Legal contracts are essentially written into code, exploring and tabulating every possible outcome or scenario of each transaction. Once all terms have been agreed upon and set by all the constituents of the network, transactions can occur automatically.[129] Smart contracts prevent the need for someone to sit at a computer and manually click that they accept or agree to conditions of a transaction every time one happens. The contracts are laid out to allow the device to test the validity of each step and automatically cue the transaction once all requirements are met and agreed upon. Blockchains can run on mobile phones, as lots of distributed banking is set up, like M-pesa in sub-Saharan Africa.[130] The finances are tracked and conducted through the smart contract by linking bank accounts to the blockchain, including repayments of loans over time, resulting in less social and economic risk for users.[131] Invoicing management over blockchain is even a solution that a major solar developer in Puerto Rico intends to utilize.[132]

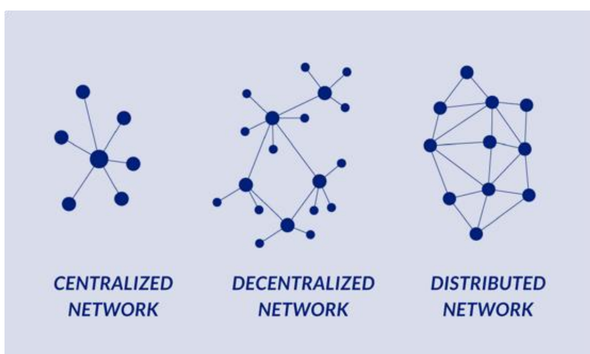
Blockchain allows processes to run faster and cut time down from administrative work due to the connections and verified communication with all the entities involved. The immense improvement of processing time offered by DLTs is supported by the evidence of purely switching to digital systems. Blockchain is not always an appropriate solution for all network improvements, as many developers and startups are trying to market. Often, simply recording transactions or data onto a computer with or without internet access can greatly increase processing accuracy and efficiency,

[129] Bronder, 2017.
[130] Safaricom. "M-PESA." Accessed 2017.
[131] Ibid.
[132] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

particularly in systems that are still mostly paper based like vaccine records in rural developing areas for example.[133] Even so, the best way to determine if a solution will work is to go through the design process with those who will use the technology. The methods of this thesis emphasized communication and interviews with people working in the field on the ground. With the underlying infrastructure of trust, increased speed in decisions and transactions is entirely possible. Blockchain's value can most be exercised through streamlining administrative work like managing invoicing.[134,135] Connecting to internet-connected smart devices, also known as the Internet of Things (IoT), can also contribute to the verification process. While both these technologies are currently buzzwords, blockchain will be at its peak when it is so widely used in administrative work that the excitement is forgotten. People could realize it is not a flashy system, but rather it is purely a faster and more trustworthy platform on which to conduct cryptographed transactions.

<u>Energy: Centralized vs. Decentralized vs. Distributed</u>

Figure B: Visualization of Three Networks



"UN Supports Blockchain Technology for Climate Action." UNFCCC. January 22, 2018. Accessed January 2019. https://unfccc.int/newsun-supports-blockchain-technology-for-climate-action.

[133] Gous, N., D. I. Boeras, B. Cheng, J. Takle, B. Cunningham and R. W. Peeling. "The impact of digital technologies on point-of-care diagnostics in resource-limited settings." *Expert Review of Molecular Diagnostics* 18, no. 4 (2018): 385-397.
[134] Bronder, 2017.
[135] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

Centralized System in Puerto Rico

The unique aspects of distributed networks are at the heart of energy innovation. Centralized networks are like the national grid, operated by one main entity. Centralized systems are often created in order to execute plans faster with less bureaucracy, yet that centralized efficiency is limited by the will and motivation of the controlling entity to expand their network and increase inclusion.[136] When that centralized player is a government energy provider like PREPA who already faces operating and financial constraints, expansion to provide more reliable and cleaner electricity to greater numbers of people is not necessarily the highest priority. Furthermore, when that central entity is inefficient and insufficient at fulfilling the job, then the main benefit of centralized systems is completely lost or coopted by the managing authority, historically limiting benefits to the wealthiest and most powerful in a society.

Utilities Power Centralized Grids

In Puerto Rico, the energy system is a centralized one run by the Puerto Rico Electric Power Authority, the government utility. The U.S. EIA categorizes utility scale to be over 1 MW in total nameplate capacity,[137] which is the amount of energy generation a power plant has the equipment to produce. Due to fluctuations in conditions, the capacity may not be equal generation at all times. On the utility scale for solar PV power plants, the majority in the U.S. are actually 5 megawatts or smaller.[138] Exposed through analysis of Puerto Rico's utility generation capacity, by November 2018, only 6.8% of equipment for utility scale power was for solar [Figure G]. Among that utility solar, only 39.2 MW of the 145.4 MW nameplate capacity of solar was operational [Figure G]. One may believe that these numbers reflect recovery from the 2017 hurricane season, however they do not.

[136] Sowerwine, Charles. *France since 1870: Culture, Politics and Society*. London: Palgrave, 2018.
[137] U.S. Energy Information Administration. "Most U.S. Utility-scale Solar Photovoltaic Power Plants Are 5 Megawatts or Smaller." February 7, 2019. Accessed March 2019.
[138] Ibid.

This same source only began collecting monthly electric generator inventory data from Puerto Rico in March 2018,[139] yet the historical record of electricity service in Puerto Rico reveals that fossil fuels have always been dominant.[140]

While many utility-scale power generators are not owned by the government, the grid is maintained and operated by PREPA and suffers extensive losses. Grid systems can work in many contexts and countries. However, in Puerto Rico, being connected to the grid actually can be a liability and a risk of producer loss of generated energy and risk of inconsistent supplies leading to black and brownouts endured by customers. Therefore, when there are power outages and the grid is not running, no matter the quality of source, management, or equipment of the utility, electricity is lost. Victor Gonzalez, the founder of WindMar Group, a Puerto Rican renewable energy company that develops wind and solar for both residential and commercial projects and operates a 10 MW solar utility,[141] shed light on the different sources of electricity loss on the government transmission lines. In answering questions, Mr. Gonzalez wrote that: "In Puerto Rico the difference between energy generated at the powerplants and actual energy sold at the customer meters is 20%. This is high. 6 to 8% is theft. The other 12% to 14% are the transmission, distribution and generation losses. Transmission is around 4 to 6%."[142] These numbers mean that of the 20-22 million kWh Mr. Gonzalez's solar plant produces every year, only 16 million kWh are available for the end-user. By Mr. Gonzalez's estimate that average annual residential electricity consumption is 5,000 kWh, the losses from grid transmission and distribution mean that 3,200 households instead of 4,000 households can be serviced through his power plant. The reality of extreme inefficiency of grid distribution suggests the necessity for system-wide reconstruction. On a grid that losses 20% of its

---

[139] U.S. Energy Information Administration. "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a Supplement to Form EIA-860): March 2018." December 2018. Accessed January 25, 2019.
[140] Autoridad De Energía Eléctrica (PREPA), 2019.
[141] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[142] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.

electricity, not only do a greater quantity of fossil fuels need to be burned into order to fulfill the same demand. This also disincentivizes developers from building more renewable energy infrastructure. Anyone connected to the Transmission Center (TC) of the grid will lose revenues for reasons out of their control. Since PREPA runs the Puerto Rican grid, the depth of their debt could in part originate from loss of revenues due to the low efficiency and periodic dysfunction of energy generation and distribution facilities.

The complex physics behind transmission, distribution, and generation losses can in short be explained due to distance.[143,144,145,146] System losses occur through cables and converters, and the length of cables as well as voltage is correlated with greater losses.[147] Shorter distances use AC transmission systems, and new large energy projects are looking into installing high voltage direct current (HVDC) and high voltage alternative current (HVAC) solutions that have the lowest transmission losses.[148] These high voltage systems are not entirely necessary for the insular island of 9,000 square kilometers, since no singular power plant intends to run a transmission line across the length of the island, as utilities service entities in their vicinities. The rate of improvement of transmission technology is still notable for the potential future of Puerto Rico's energy system. The risk of losing large percentages of generated energy by merely connecting to a centralized grid system heavily supports the building of a complementary newer, more efficient, more protected, and more decentralized energy distribution network.

Decentralized System in Puerto Rico

[143] Negra, N. Barberis, J. Todorovic, and T. Ackermann. "Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Wind Farms." *Electric Power Systems Research* 76, no. 11 (2006): 916-27.
[144] Delucchi, Mark A., and Mark Z. Jacobson. "Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies." *Energy Policy* 39, no. 3 (2011): 1170-190.
[145] Vrana, Til Kristian, and Olve Mo. "Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables." *Energy Procedia* 94 (2016): 399-408.
[146] "Distance Transmission." *ScienceDirect Topics*. Accessed March 2019.
[147] Delucchi, 2011.
[148] Delucchi, 2011.

Recognizing these shortcomings of a centralized network and the importance of electricity access to improve quality of life, many companies, energy developers, nonprofits, researchers, and governments began looking into more decentralized energy networks like community solar.[149,150,151] In the decentralized model, there is not one controlling group. Instead, there could be several hubs that connect to smaller communities. Decentralized systems can contribute to beneficial development of emerging markets, where centralized systems have similar characteristics to Puerto Rico's. In Madagascar, researchers found that transferring power from the central government to the local government would increase rural communities' management of their own expenses and financial resources, which can improve local economies.[152]

Decentralized systems can be a great solution for neighborhoods of residents who want locally generated renewable energy yet do not own their building of residence and may face restrictions to rooftop installations. A ground-mounted solar array, for example, could then serve nearby buildings, who may still be connected to the grid, creating a network with several central points as shown in Figure B. Having hybrid networks is particularly beneficial to have more resilience in any field, yet several main concerns remain. With many different central points in the decentralized network, verification and trust among all the parties is not easy to guarantee.

In the energy sector, decentralized systems for renewable energy often take the form of PV rooftop arrays with battery capacity systems or community solar. Both of these options place the electricity generator in closer proximity to the consumer yet can still be connected to the grid. Solar developers in Puerto Rico like Mr. Gonzalez and Mr. Torres offer photovoltaic and batter installations for clients. The benefits of batteries are absolutely clear when it comes to renewable energy like solar. Half of Puerto Rico's energy consumption occurs in "night hours," or around

[149] "About Us." *Windmar PV.* Accessed December 2018.
[150] O'Malley, 2017.
[151] Maximo Solar Industries. "Maximo Solar Industries." *Maximosolar.com*. Accessed January 2019.
[152] Ravelohery N. Tahina. "Decentralization: Problems and Solutions - Madagascar Evidence." *Journal of Economics and Finance* 6, no. 2, (2015):1-9.

when the sun begins to go down and solar panels no longer generate electricity.[153] Batteries as a form of energy storage are increasingly important to the rise of renewable energy installations worldwide.[154] Storage options also provide the sense of coverage and reliability that people desire from energy systems, and so those who are able to pay often opt to include battery installations.[155] Battery storage technology is one of the most important innovations in the field of renewable energy, yet the PV and batteries must be well-maintained and are not quick fixes to all energy problems. Batteries have their own transmission, distribution, and storage losses, and Puerto Rico solar installer altE Store states:

> "Due to the way that AC Coupled systems, like our battery backup kits, charge the batteries, a large battery bank is needed to prevent overcharging and damaging the battery bank. We do not recommend using a smaller bank than this. For long life, batteries like to be charged at a certain rate. If they are charged with too much current, they can become damaged by trying to charge too fast. If they are charged with too little current, the battery bank will not be fully charged and will suffer an early death from sulfation, where crystals form inside the battery."[156]

The balance of equipping one house with the proper amount of battery storage is critical for the health of the system. If each residence requires a large battery system, however, costs increase. Education of these specificities is also not well-dispersed. Batteries are not like oil-powered generators that people often seek once power is shut off[157] that can be turned on after months of no use. Batteries are a solution to using more of the generated electricity from renewable energy sources, particularly at night. However, decentralized systems with batteries need to be extremely sensitive to the scale of the electricity system and the necessary balance could be hard to achieve with just a singular residential household's consumption. It is not the best idea to place an expensive,

[153] "How to Calculate Your Solar PV System - Maximo Solar." Accessed February 2019.
[154] Parra, David, and Martin K. Patel. "The Nature of Combining Energy Storage Applications for Residential Battery Technology." *Applied Energy* 239 (2019): 1343-355.
[155] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[156] "Battery Backup for Puerto Rico's Grid Tied Solar Power Systems." 2018.
[157] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.

sensitive, and aging piece of equipment in every single home and building when storage capabilities could be shared among neighborhoods.

Puerto Rico houses don't need extreme amounts of solar power to fully cover their demands,[158,159] and batteries are a high capital and cost barrier to entering a decentralized energy network.[160] The global trend of PV self-consumption is also still quite isolated. Singular residential, commercial, or public buildings are undergoing individual retrofitting for renewable energy, often solar roof systems without consideration of energy connections to neighbors. Previously, there had been no evolved marketplace for neighbors to connect to one another, and so either grid dependency or self-sufficiency were the available pathways. Those days of polarized connection have come to an end with the development of open source platforms and the realization that diverse networks are more resilient and reliable. The isolated nature of decentralized solar PV and battery systems can be expensive and still have considerable energy loss. While decentralized energy networks do guide people to install more small-scale renewable energy, the mechanics behind the decentralized system could be smoother and more connected.

Distributed System in Puerto Rico: Peer to Peer Energy Trading

Distributed networks aim to replicate the efficiency of decision making in ideal centralized systems and the more equitable balance of power in decentralized systems. Considering these three fundamental network shapes, certain regions or industries may benefit more from one type or another. Energy is widely regarded as one of the best areas that distributed networks can uplift and build out. Puerto Rico is a solar-rich, urban, energy dependent, underdeveloped island with an

[158] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[159] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[160] Parra et al., 2019.

unreliable electricity grid. Several of these characteristics resonate with many other areas in the world that could benefit from distributed solar energy systems.

Peer-to-peer energy trading is the epitome of a distributed and connected energy system. As a distributed system, blockchain adds immense value by supporting the set-up of smart contracts and transactions to make electricity purchase and sale smoother, faster, with less paper work, and with fewer costs. Tying in finance, community resilience building, and renewable energy expansion, peer-to-peer (P2P) is the most interesting and successful example of blockchain in the energy and utility sector. What P2P systems actually set up are direct trades between entities by connecting people with renewable energy assets like solar panels to buy and sell electricity directly with their neighbors, bypassing middlemen.[161] In the case of energy, the middlemen are utilities. In grid systems that allow energy producers to sell to the grid, a residence may sell unconsumed electricity to the grid for another's consumption. Due to the large scale – and therefore greater assets, market access, and bargaining power – of utilities, the centralized power supplier could buy the excess at a low price and then sell to end users at high rates. P2P cuts away the bargaining and instead gives the consumer a better price per kWh and puts more money into the hands of the renewable energy asset owner, which could help with paying off the system faster [Table 1].

Trials of peer-to-peer energy trading are spreading around the world, from Brooklyn to Bangladesh. One the first neighborhood trials of P2P was the Brooklyn Microgrid, connecting a geographically tightknit group in an urban area,[162] the perfect test group. Another startup pursuing blockchain-based energy trading is ME SOLShare. Based in Bangladesh, ME SOLShare is working to connect the people with solar panels together to improve electricity access, market participation, and peoples' livelihood.[163] Models like these ones hold high growth potential, since over four million

[161] Bronder, 2017.
[162] Peck, Morgen E. "A Microgrid Grows in Brooklyn." *Scientific American*. April 22, 2016. Accessed August 2017.
[163] Bronder, 2017.

homes in Bangladesh have already been retrofitted with solar and numbers are growing worldwide.[164] "Access to electricity has major implications for alleviating poverty including prolonging the hours that people can be productive, whether for work or education,"[165] and the inclusive distributed model of P2P energy trading allows for easier entrance into a network that is exterior of the national grid.

Electricity storage is still an important part of the distributed energy network; however, costs and potential battery waste can be minimized in a peer-to-peer trading system. Through interviews with Puerto Rican solar developers, each roof installation could easily supply 80-100% of each household's own demand.[166] The use of batteries in this system would be to capture electricity to use at night. If an entire community is connected, where some buildings have batteries and some don't, then personal batteries would not be necessary for every family, significantly making this a more affordable option to join the network. Larger battery banks could reside in bigger community centers such as schools and hospitals and provide night-time electricity to nearby residencies. P2P networks are not exclusive to residential buildings. Adding commercial buildings and commercial-sized solar assets to a distributed trading network could add the resiliency that fluctuating energy demands of any community would need.

Not only will distributed systems improve resilience to unreliable grids and harsh weather events through increasing renewable energy generation capacity and diversifying source location, but also solar system demand will increase and provide more economic benefits to the island. The RMI identifies that "a full transition to renewable energy and microgrid resiliency in Puerto Rico will produce thousands of new jobs in engineering, construction, maintenance, and operations."[167] After

[164] Yee, Amy. "In Rural Bangladesh, Solar Power Dents Poverty." *The New York Times*. October 04, 2016. Accessed August 2017.
[165] Bronder, 2017.
[166] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[167] O'Malley, 2017.

the hurricanes, solar developers are conscious of their access to supplies.[168] Solar equipment manufacturing has been slowly transitioning to be located on Puerto Rico for easier access to panels and inverters for speed of construction and development.[169,170] Through bringing a growing market of solar sales to the island, solar energy could be the way forward towards an economically, electrically, and environmentally sustainable recovery from debt and destruction.

Distributed ledger technologies and distributed energy networks are seen as incredibly useful to the present and future of climate action. The Rocky Mountain Institute identifies other locations that are currently benefiting from a more diverse network of electricity sourcing. In RMI's project to rebuild resiliency in Puerto Rico, they explain that a new grid designed to incorporate distributed generation from "rooftop solar, solar parking lots, solar farms, solar on brown fields, on-shore wind, off-shore wind, and the latest technology for storage capacity is more reliable and more resilient to extreme weather and monster hurricanes."[171] Countries such as Denmark, Costa Rica, and Ecuador have all pursued and successfully achieved 100% renewable energy use, increasing their own energy independence and security.[172] Closer to home for Puerto Rico, islands such as "Ta'u in American Samoa, Bonaire in the Dutch Antilles, and Kaua'i in the Hawaiian chain have all shown the capacity to thrive on renewables."[173] Furthermore, the United Nations Framework Convention on Climate Change (UNFCCC), a UN secretariat also nicknamed UN Climate Change that "provides technical expertise and assists in the analysis and review of climate change conformation"[174] published an article in support of DLT use for climate action. The UNFCCC identified that DLT and blockchain could:

- strengthen monitoring, reporting and verification of the impacts of climate action
- improve transparency, traceability and cost-effectiveness of climate action

[168] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[169] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[170] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[171] O'Malley, 2017.
[172] O'Malley, 2017.
[173] O'Malley, 2017.
[174] "About the Secretariat." *UNFCCC*. Accessed March 2019.

- build trust among climate actors
- make incentive mechanisms for climate action accessible to the poorest
- support mobilization of green finance.[175]

Conclusion of Networks

Examining how each network type materializes in the energy sector leads to the conclusion that distributed is the most resilient for Puerto Rico. Blockchain use in the energy sector is not an isolated push for innovation for the sake of innovation. The benefits are widely recognized by solar developers, NGOs, governments, and international organizations. More research is expanding to test blockchain-incorporated energy projects.[176,177] In an interview with Alejandro Uriarte of New Energy, one of the top five solar developers in Puerto Rico, he disclosed plans to develop a new peer-to-peer solar energy network in Roosevelt Roads on the western part of Puerto Rico.[178] Construction of this project will begin in the summer of 2019 and likely be completed at the end of the 2020 calendar year. Peer-to-peer energy trading is a valid and exceptional solution to enable community-owned energy economies, and entities are already working to expand this distributed energy network in Puerto Rico.

Building Distributed Solar Networks in Puerto Rico

To test out how distributed networks could improve energy systems, this thesis conducts an extensive comparison and analysis of electricity management and the energy context in Puerto Rico. This analysis provides evidence and support that distributed solar systems are the most apt solution to problems of energy availability, resilience post-natural disaster, cost to consumer, and transmission efficiency. Complex systems of distributed ledger technologies and peer to peer trading

[175] "UN Supports Blockchain Technology for Climate Action." *UNFCCC*. January 22, 2018. Accessed January 2019.
[176] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[177] "OpenSolar." *Yale OpenLab*. Accessed March 2019.
[178] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

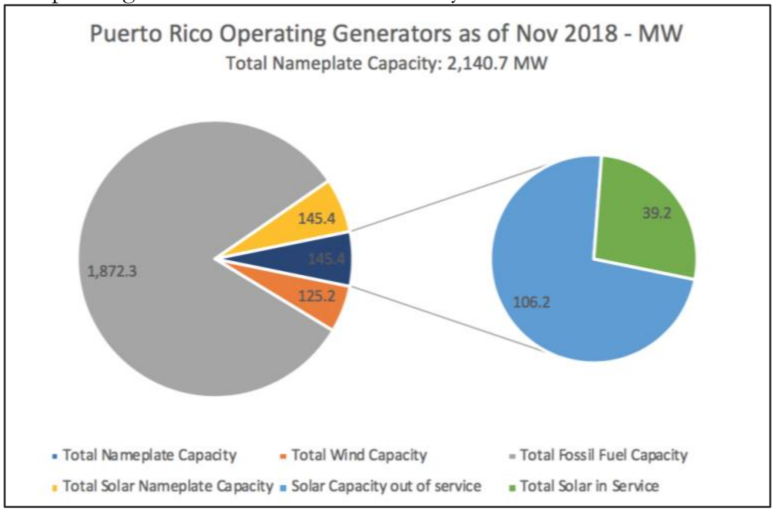
for energy would work in Puerto Rico specifically for the factors of power production and consumption, urban density, and schools within communities. In depth analysis of U.S Census and EIA data reveal the physical and electrical feasibility of distributed solar for Puerto Rico. Adding to the data analysis, the creation of a financial model to analyze the feasibility of this energy network tests the outcomes of financial options to set up Puerto Ricans for more power and financial sustainably. When solar offers the opportunity to build an energy system that is entirely renewable, more resilient to hurricanes, cheaper to install, cheaper per kWh for consumers, less environmentally polluting, places ownership of energy assets into the hands of people, captures a free and unending supply of electrons, and produces thousands of new jobs on the island, the choice to develop is seemingly obvious. The biggest roadblocks to achieving 100 percent renewable and reliable energy for all 3.3 million residents are the political will, financing options, involvement of innovators and the private sector, and the disaster mindset of building bandages to systemic problems. Approaching the rebuilding from the systems level rather than only correcting small-scale issues will set Puerto Rico up for faster recoveries when faced with future natural disasters. Systems rebuilding can take many forms, but the results of the data analysis show that focusing on community interconnection and approximal electricity transmission among close neighbors will work for Puerto Rico.

Factor 1: Power Production and Price (Results)

Gap in Functioning Utility-Size Solar

Puerto Rico already has interested and planned peer-to-peer energy projects on the rise, yet concrete analysis becomes a tangible supporting factor for how and why these distributed networks will benefit the people and the environment. Within the U.S. EIA's collected data in Puerto Rico from November 2018, it is clear that there is gap in functioning utility-sized solar. Larger scale solar is emerging on the island, yet Figure G shows not only just how small of a percentage that is in relation to all of the utility-sized capacity but also reveals the misuse and malfunction of those power plants. Of the 2,140.7 MW of total nameplate utility capacity, 145.4 MW is solar, 125.2 MW is wind, and 1,872.3 MW is fossil fuels including petroleum liquids, conventional steam gas, and landfill gas.[179] Only 39.2 MW, or 27%, of the total solar capacity was in service at the time of data collection.[180] PREPA's solar generation doubled in six months from October 2016 to April 2017 after the hurricanes, yet renewables still only make up 2.4% of PREPA's energy breakdown.[181] Far from PREPA's 2010 Renewable Portfolio Standard Goals of achieving 12% electricity from renewables by 2015, 15% by 2020, and 20% by 2035,[182] Puerto Rico needs much more investment and dedication to maintenance of the installed capacity to rebuild a sustainable energy system.

Figure G: The Operating Power Generation at the utility scale in Puerto Rico as of November 2018



U.S. Energy Information Administration. "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a Supplement to Form EIA-860): November 2018."December 2018. Accessed January 25, 2019. https://www.eia.gov/electricity/data/eia860m/.

Losses in the System: Transmission and Theft

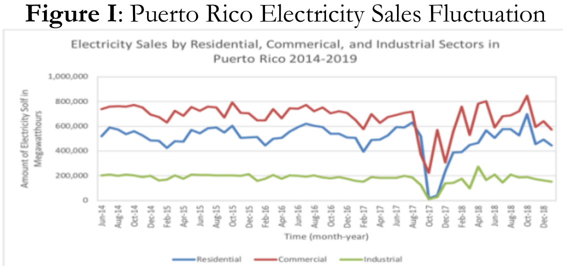
The loss of function of around 73% of installed utility-sized solar generation is made worse by the vast losses from transmission and theft. Despite PREPA's efforts to increase capacity in order to meet their 2010 Goals, of the 68 long-term public-private partnerships (PPPs) with solar, wind,

179 U.S. Energy Information Administration. "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a Supplement to Form EIA-860): November 2018." December 2018. Accessed January 25, 2019.
180 Ibid.
181 U.S. Energy Information Administration. "Puerto Rico: Territory Energy Profile Data." 2019.
182 Ibid.

and biomass energy developers signed, 11 were built, 10 were canceled, and 47 contracts are currently inactive or in the process of renegotiation.[183] Increase in renewable capacity is certainly critical to Puerto Rico's stability and success, however the 20% total loss in transmission and distribution must be addressed to improve efficiency and energy security. One solution to the transmission losses, as stated earlier, is to decrease the distance between the source of generation and the end user.[184,185,186,187] The easiest way to do this is to install rooftop solar. Theft would also likely decrease when distribution lines physically span less open space. In P2P networks, potentially linked with surveillance devices, tighter-knit communities could suffer less theft with increased security. A likely factor in the incentive for grid theft is the price of electricity per kWh in Puerto Rico. Therefore, constructing more inclusive, community-based energy generation and consumption networks will provide a lower-cost platform to legally access clean electricity.

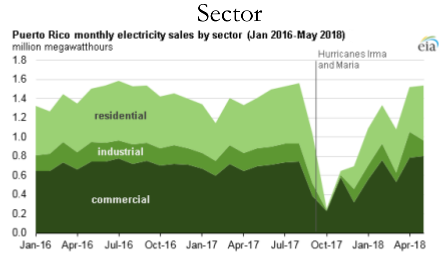
Economic Standing of Electricity

Figure I: Puerto Rico Electricity Sales Fluctuation



U.S. Energy Information Administration. "Electric Power Monthly." EIA Independent Statistics and Analysis. March 26, 2019. Accessed March 2019. https://www.eia.gov/electricity/monthly/index.php.

Figure H: Puerto Rico Monthly Electricity Sales by Sector



U.S. Energy Information Administration. "EIA electricity sales data for Puerto Rico show rate of recovery since hurricanes." *EIA.* August 6, 2018. Accessed December 2018. https://www.eia.gov/todayinenergy/detail.php?id=36832.

One of the biggest limitations to grid-tied electricity consumers and simultaneously one of the best drivers for innovation is the egregiously high cost of electricity in Puerto Rico. Using data collected by the U.S. EIA, it becomes clear that Puerto Rico would benefit from new energy system

---

[183] Ibid.
[184] Negra, N. Barberis, J. Todorovic, and T. Ackermann. "Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Wind Farms." *Electric Power Systems Research* 76, no. 11 (2006): 916-27.
[185] Delucchi, Mark A., and Mark Z. Jacobson. "Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies." *Energy Policy* 39, no. 3 (2011): 1170-190.
[186] Vrana, Til Kristian, and Olve Mo. "Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables." *Energy Procedia* 94 (2016): 399-408.
[187] "Distance Transmission." *ScienceDirect Topics*. Accessed March 2019.

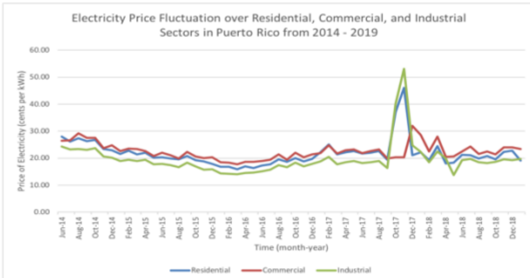
to increase electricity price stability and ideally lower the overall cost of energy on the island. Figure H depicts the changes in monthly energy sales in Puerto Rico before and following the landfalls of Hurricanes Irma and Maria. The extreme dip is not unexpected, since the entire island suffered power losses. Figure H is supported by and replicated in Figure I, created from the raw data on electricity sales in megawatt hours from the U.S. EIA. The critical aspect of this graph is that at the lowest point, only commercial entities were purchasing power. Furthermore, the residential sector had a much slower recovery as compared to commercial. These aspects show the extreme vulnerability of the residential sector.

It must be noted that the interpretation of this data is conducted through analysis from EIA's data provided in excel format. Original analysis was conducted on the data released from February 2019 and has been updated to reflect the EIA's release of updated data from March 26, 2019.[188] The update and distinction is notable, as updated data may be available after the submission of this thesis.[189] Minute differences in numbers of revenue, sales, customers, and price may be present across several mediums of published data. Numbers are final for 2017 and still marked as preliminary for 2018,[190] yet this is still a good indicator of these variable in Puerto Rico at that time.

[188] U.S. Energy Information Administration. "Monthly Form EIA-861M (formerly EIA-826) Detailed Data (1990 - Present)." EIA Electricity Data. March 26, 2019. Accessed March 26, 2019.
[189] U.S. Energy Information Administration. "Electric Power Monthly." EIA Independent Statistics and Analysis. March 26, 2019. Accessed March 2019.
[190] U.S. Energy Information Administration. "Monthly Form EIA-861M (formerly EIA-826) Detailed Data (1990 - Present)." 2019.

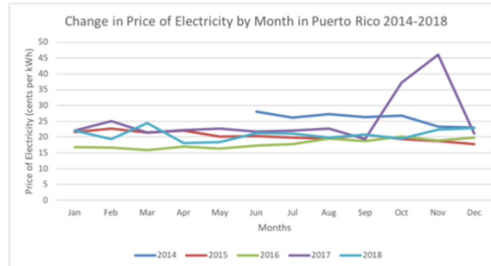
Price of Electricity

Figure J: Puerto Rico Electricity Price Fluctuation



U.S. Energy Information Administration. "Electric Power Monthly." EIA Independent Statistics and Analysis. March 26, 2019. Accessed March 2019. https://www.eia.gov/electricity/monthly/index.php.

Figure P: Puerto Rico Change in Electricity Price by Year (2014-2018)



U.S. Energy Information Administration. "Monthly Form EIA-861M (formerly EIA-826) Detailed Data (1990 - Present)." EIA Electricity Data. March 26, 2019. Accessed March 26, 2019 https://www.eia.gov/electricity/data.php#sales.

The U.S. EIA's data on Puerto Rico's monthly electricity data exposes the price vulnerability and comparatively high costs. Figure J depicts the change of price by sector in cents per kWh for electricity in Puerto Rico from mid-2014, when the EIA began collecting data, to December 2018.[191] Massive spikes in cost are seen in October and November of 2017 with prices then balancing out to pre-hurricane levels [Figure P]. The average residential price of electricity in Puerto Rico was 25.83 ¢/kWh in 2014, 20.36 ¢/kWh in 2015, 17.89 ¢/kWh in 2016, 25.29 ¢/kWh in 2017, and 20.83 ¢/kWh in 2018. Over the entire timeline of data collection, the average residential price of electricity was 21.65 ¢/kWh. The average commercial price per month spanning 2014 to 2018 was 22.46 ¢/kWh. The average industrial price per month spanning 2014 to 2018 was 19.57 ¢/kWh. These results are visualized in Figure J. The average residential, commercial, and industrial prices of electricity for all states in the U.S. since June 2014 are 13.41 ¢/kWh, 10.97 ¢/kWh, and 7.97 ¢/kWh. Based on these results, slightly higher residential prices are common across the U.S. Every sector was hit extremely hard by the hurricanes. Greater generation capacity both from new construction as well as from re-servicing of existing power plants will likely drive the prices lower than 2017 and 2018 levels.

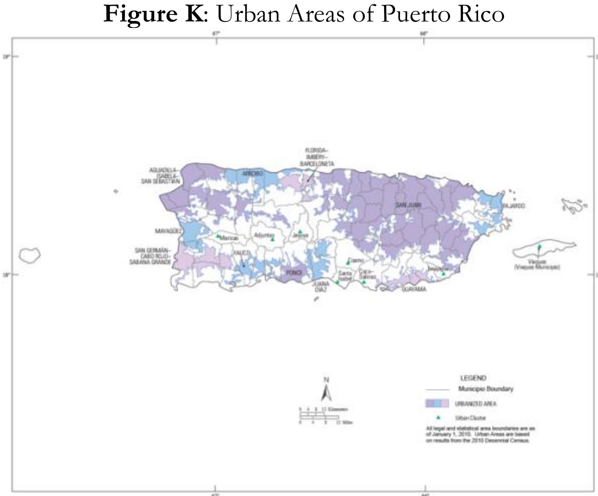
[191] Ibid.

Puerto Rico's 2015 average price of electricity was still 1.53 times higher than the residential average 2015 price of 13.26 ¢/kWh across all states. Import costs are likely the main reason for high prices. Since PREPA relies on fossil fuels that do not come from the island for 69% of their energy generation[192] and it is expensive to ship barrels of oil, the transportation costs are reflected in the electricity price. Striving for energy independence would be one way to alleviate Puerto Rico of the high electricity costs. Puerto Rico's residential electricity price reached a maximum at 45.99 ¢/kWh. The maximum cost for electricity achieved in a U.S. state was 40.16 ¢/kWh in Hawaii in 2012. Since then, Hawaii has led a push towards energy independence through renewable energy. Prices remain high in Hawaii, resting around 30.68 ¢/kWh, as indicated by the June 2014 to January 2019 average from EIA data. Islands have an incredibly difficult and costly time acquiring energy from the mainland U.S. Puerto Rico is closer to Florida than Hawaii is to California by a factor of 2.44.

Factor 2: Urban Density as Building Ground for Distributed Networks

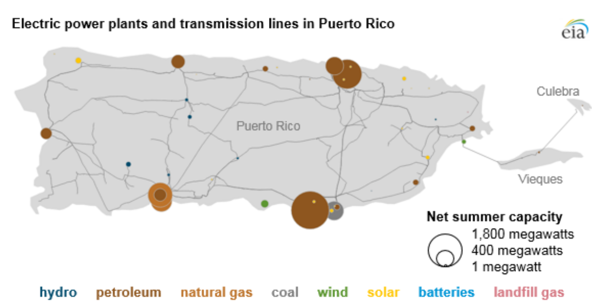
Urban Proximity

Figure K: Urban Areas of Puerto Rico



U.S. Census Bureau. "Puerto Rico: 2010 - Population and Housing Unit Counts - 2010 Census of Population and Housing." U.S. Department of Commerce. (2012).

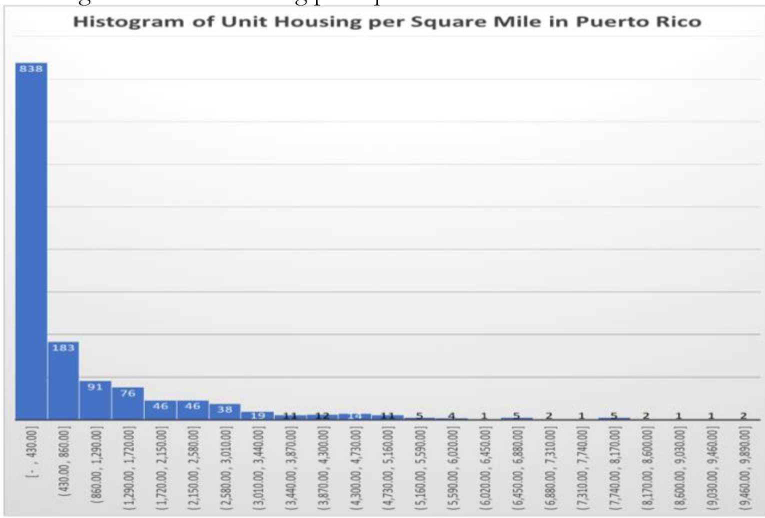
Figure L: Map of Electric Power Plants and Transmission Lines in Puerto Rico



U.S. Energy Information Administration. "EIA adds Puerto Rico data to its U.S. power plant inventory." EIA. July 9, 2018. Accessed December 2018. https://www.eia.gov/todayinenergy/detail.php?id=36613.

192 Autoridad De Energía Eléctrica (PREPA), 2019.

Figure M: Histogram of Unit Housing per Square Mile in Puerto Rico from U.S. Census Data



Data from the U.S. Census report was converted into a Microsoft Excel medium to allow for data analysis. U.S. Census Bureau. "Puerto Rico: 2010 – Population and Housing Unit Counts - 2010 Census of Population and Housing." U.S. Department of Commerce. (201).

Distributed energy networks will function well in Puerto Rico due to the urban density of the island. Figure K, from the 2010 U.S. Housing Census, shades the urbanized areas of the island.[193] The graph indicates potential areas in which to build systems of rooftop solar connected to neighboring buildings. The proximity of buildings makes a strong case for building small-scale rooftop solar. Once energy systems are connected to each other, transmission losses would be minimized due to decreased distance between generation source and consumer. Figure L reveals the electric power plants and transmission lines in Puerto Rico, showing that the large-scale powerplants are, understandably, located in the areas with highest urban density when compared to Figure K. The transmission lines stretch long areas of the island, including out to the islands of Vieques and Culebra. Building a distributed solar network as a complementary system to the grid and transmission lines would improve energy resilience and independence for all the islands.

A P2P system is made possible by the proximity of housing units, and could service the urban or semi-urban areas that do not have access to power plant transmission lines. Figure M shows a histogram of housing units per square mile in all of Puerto Rico, analyzed from 2010 census

[193] U.S. Census Bureau. "Puerto Rico: 2010 - Population and Housing Unit Counts - 2010 Census of Population and Housing." *U.S. Department of Commerce*. (2012).

data. The Census Bureau surveyed Puerto Rico's 78 municipios, 902 municipio subdivisions, which consist of 827 barrios and 75 barrios-pueblo.[194] The housing density average across the entire island, calculated by dividing the total number of housing units by the land area of the island, is 478.10 housing units per square mile.[195] That is, however, perhaps not the most telling metric, as not every part of Puerto Rico is inhabited by humans, and access to residential electricity is more important in areas where people live. The number of housing units increased from the 1990, 2000, and 2010 censuses,[196] indicating that Puerto Rico is also following the global trend of urbanization. Of the 1414 divisions surveyed, the average of all the housing densities is 1,171 and the median is 543.9.[197] The histogram shows that of the 1414, there are 838 in the 0-430 housing density range, 183 areas with 430-860 housing units per square mile, and 2 areas with 9,460-9,890 density, among other ranges.[198] The highest housing density is unsurprisingly found in the urban zone of San Juan, the territory's capital. The lowest housing density is in the Cedro barrio. A blockchain-based energy trading system does not require incredibly high housing density, as projects such as the Brooklyn Microgrid are operating with around or fewer than 100 buildings.[199] Given the urban density of Puerto Rico, a peer-to-peer solar distributed network would viably connect rooftop solar systems in close proximity to streamline the administration and payment processes behind electricity purchase and grow a network of energy independent neighborhoods of Puerto Rico who own their own generation equipment.

194 U.S. Census Bureau, 2012.
195 U.S. Census Bureau, 2012.
196 U.S. Census Bureau, 2012.
197 U.S. Census Bureau, 2012.
198 U.S. Census Bureau, 2012.
199 Peck, 2016.

Lack of Net Metering

Puerto Rico's grid does not currently incorporate small-scale renewable energy net metering, making the island an important place to build distributed networks. Peer-to-peer energy trading, on a surface level, operates as net metering system that is financially more beneficial to both the producer and consumer. Net energy metering is the process by which electricity generators can feed their excess production into the centralized grid in return for credits that they can redeem for grid electricity later when needed. This can be viewed as a way to store electricity since the generated kWh from a building's solar panels wouldn't have to be used immediately. However, the renewable energy kWh units are likely to be consumed by another grid consumer, and the electricity the original building eventually uses may come from fossil fuels. Sometimes grids will pay the producers for electricity rather than provide credits. Overall, net metering from many sources could supply enough electricity to decrease the need for fossil fuel power plants generations at certain times in the day. Net metering would operate smoothly in an area with a reliable and well-functioning grid, but in Puerto Rico would still run in to the problems facing PREPA's grid.

Mr. Uriarte expressed frustration at Puerto Rico's lack of net metering. The national grid currently will not buy excess solar or other renewable power from systems that are less than 25 kW in capacity.[200] The average residential solar system in Puerto Rico is 5 kW in nameplate capacity and is not granted the permit required to sell electricity to the grid. When asked what he sees as the biggest barrier to increasing renewable energy across the whole island, Mr. Uriarte spoke about how increased connectivity of small scale solar could deploy solar electricity more quickly. The solar industry in Puerto Rico is pushing to pass a new law to be connected to the grid to supply more stable streams of electricity and ideally decrease brownouts across the island. For systems greater than 25 kW of solar, Mr. Uriarte hesitantly confirmed that PREPA is obligated to provide

[200] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

connectivity and net metering. Even if the solar industry's lobbying is successful, the prices at which PREPA or other utilities will accept excess solar are likely not the best financial deal for the generators. If Puerto Rico follows the credit-based net metering system the solar electricity prosumer would not have the opportunity to monetize their electricity generation and would lose the ability to reallocate any income from selling electricity to potentially pay off the costs of their solar system or make other choices about their own finances. For residences without on-site battery storage, the credit system could cover nighttime electricity demand. A distributed system that includes a proportion of buildings with battery systems, however, could provide the same nighttime supply while relying only on renewables and offering the producers tangible money and the consumers a lower price per kWh than Puerto Rico's grid.

Using Community Centers: Schools

Schools could be the connecting factors that allow these grid-alternative distributed networks to have battery storage that can serve all the connected prosumers. During the hurricanes, schools and hospitals were prioritized for generators and select microgrid energy use, as they were communal shelters for those who lost power or their homes.[201] Now, they are the target of several post-hurricane rebuilding initiatives, further reinforcing the position of schools in Puerto Rico as community centers. RMI, Save the Children, and the Kinesis Foundation inaugurated a 15 kW solar PV array with a 34 kWh lithium-ion battery system for a public elementary school, and they intend to expand to schools in the 12 most-impacted municipalities from Hurricane Maria.[202] Solar PV systems are also an incredible hands-on learning opportunity for students in those communities, and the presence of solar at the schools could show more of the population the benefits of distributed

[201] Acevedo, Nicole. "Why Does Restoring Full Power in Puerto Rico Seem like a Never-ending Task?" *NBCNews.com*. February 19, 2018. Accessed March 2019.
[202] "Public School Renewable Microgrid Opens in Orocovis." *Rocky Mountain Institute*. September 27, 2018. Accessed February 2019.

renewable energy.[203] If the schools are incorporated into the neighborhood P2P system, they could operate as battery banks for the community, almost akin to using the grid as storage through net metering. During the day, schools could buy excess power from residences to fill their batteries, keeping them operational and avoiding maintenance issues from lack of use or improper charge currents. Once the sun goes down and the school is no longer in session, residences without their own battery storage units and others who need more electricity can in turn buy from the schools. Incorporating schools into P2P systems therefore makes joining the network less expensive because installing individual battery storage systems becomes nonessential.

Puerto Rico's Electricity Use

On top of the gaps in electricity delivery and high prices, Puerto Rican residential electricity use paired with the proximity of housing units sets up the island to receive sweeping benefits from distributed energy trading systems. The average Puerto Rican household consumes 5,000 kWh of electricity per year.[204,205] Levels of solar panel efficiency in Puerto Rico are also strong due to new technology and strong sun exposure.[206] Since almost every house in Puerto Rico could supply 80-100% of its own consumption from rooftop solar panels alone, connection to a distributed trading network that includes several nodes with energy storage could cover the remaining 20% demand.[207,208,209]

The main consumers of energy in households are air conditioners, refrigerators, water heating, lighting, and other small appliances like computers. Air cooling takes up around 24% of

[203] "Public School Renewable Microgrid Opens in Orocovis." *Rocky Mountain Institute*. 2018.
[204] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[205] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[206] "How to Calculate Your Solar PV System - Maximo Solar." 2019.
[207] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[208] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[209] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.

household energy use in Puerto Rico due to the tropical climate.[210] In one year, refrigerators use over 1,000 kWh of electricity. Water heating tends to use around 14-15% of household energy use, making solar water heaters another great alternative energy source that are already widely used in Puerto Rico.[211] Lighting accounts for 15% of residential electricity use, and computers use over 500 kWh per year.[212] Though the energy use of appliances adds up, overall, Puerto Rican residential consumption rates are manageable by one rooftop installation of about 20 PV panels. Compared to the mainland U.S., where the average residential utility customer uses 10,400 kWh per year,[213] Puerto Rico uses less energy per household yet pays more for it. Future studies on consumer behavior in Puerto Rico could indicate if lower prices of electricity would then remove barriers for households to live at higher consumption rates. Regardless of the outcome, if that electricity is provided by renewable energy sources, then an increase in affluence and residential energy use in Puerto Rico would not negatively impact the environment and air quality as increasing consumption of fossil fuel sources would.

Puerto Rico Financing: Lack of Law & Tax Incentives, Bank Participation

Puerto Rico has proven to be an appropriate location for P2P distributed solar systems due to data on urban proximity, the grid's lack of net metering inclusion for residential-sized power, the use of school in previous recovery plans, and the ability for most houses to entirely cover their low electricity demand. When asked what the biggest challenge facing energy access in Puerto Rico is, both Mr. Torres and Mr. Uriarte cited financing. Mr. Gonzalez mentioned that all or most of Windmar's residential installations are financed with 20-year loans. While seeking a bank loan may

[210] Champagne, A., Evansen, B., Heath, C., North, T. "Puerto Rico Residential Energy: Project Proposal submitted to the Puerto Rico Energy Affairs Administration." *PREPA*. (2010).
[211] Ibid.
[212] Champagne et al., 2010.
[213] U.S. Energy Information Administration. "How Much Electricity Does an American Home Use?" *EIA Independent Statistics and Analysis*. October 26, 2018. Accessed March 2019.

be the traditional path to pay for a rooftop solar system, which could cost anywhere from $7,000 to $25,000 in Puerto Rico,[214,215,216] financial institutions in Puerto Rico are very selective. Local banks have not financed many solar projects, rather credit unions are entering that role.[217] These funders require a FICO score of 650-680 on the FICO scale of 300 to 850, which is a credit score the majority of Puerto Ricans do not have.[218] Furthermore, the process to finance an installation is very slow with exacerbated requirements and paperwork that deter customers from seeking to install solar.[219] Tax subsidies are often seen as a government tool to incentivize solar development and help finance installations, yet this is also not a viable option for most Puerto Ricans. A 30% tax deduction for solar energy systems is available, yet the recipient must pay federal taxes, which the majority of Puerto Rican residents do not.[220,221]A new system of financing solar is critical to advance the installment of distributed energy in Puerto Rico.

Financial Model

Alternative Financing: Power Purchase Agreements

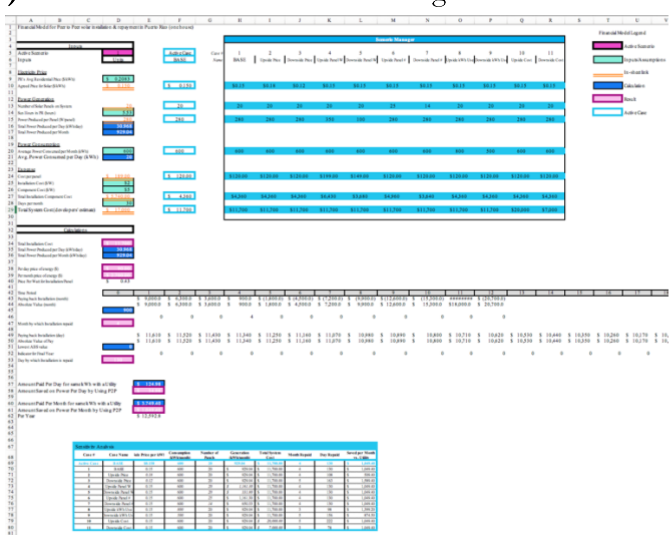
The high prices of electricity in Puerto Rico offer an opportunity for innovations in solar financing for P2P or other distributed systems while make significant cost reductions for the consumer and maintaining a sustainable business model. Power purchase agreements (PPAs) are an increasingly popular way of financing solar installations. Rather than the traditional path of acquiring a bank loan and creating a repayment plan for anywhere from seven to 20 years, power purchase agreements don't require the consumer to take on debt. Instead, "in a solar PPA, the customer pays a specified amount per kWh of generation, so the amount paid varies monthly as a function of

[214] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[215] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[216] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[217] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[218] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[219] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[220] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[221] Calderwood, Heather. "Puerto Rico - Tax Deduction for Solar Energy Systems." *DSIRE*. May 5, 2015. Accessed January 2019.

generation."[222] Solar leases operate such that "the customer pays a specified amount (agreed upon at the outset of the contract) every month, regardless of the system's energy production."[223] Over 75% of PPAs in California had no down payment or upfront cost,[224] an important quality for financing in Puerto Rico, where banks are not willing to grant the majority of the population loans for upfront costs due to credit score requirements.[225] The research by Davidson et al. reveals that while installed PV costs and price per kWh have declined greatly, as supported by Figure A, "the real contract price to the customer has remained largely unchanged" and that including residences with lower electricity expenditure, as found in Puerto Rico for example, "may require offering lower-cost contracts to homeowners."[226] Blockchain-based networks can manage the financing of solar installations as well as the subsequent sale and purchase of excess generated electricity rapidly and with minimized risk, making P2P an strong solution to the energy financing problems in Puerto Rico.

<u>Financial Model Analysis</u>

Figure N(a): Financial Model for a one-building Peer-to-Peer Solar Installation



This extends further in the excel sheet. Created from incorporating assumptions and inputs from both research cited in this thesis as well as confirmation of data points from interviews with Puerto Rican solar developers. The dynamic financial model means that the viewer can flip through all 11 scenarios by typing the

[222] Davidson, Carolyn, Daniel Steinberg, and Robert Margolis. "Exploring the Market for Third-party-owned Residential Photovoltaic Systems: Insights from Lease and Power-purchase Agreement Contract Structures and Costs in California." *Environmental Research Letters* 10, no. 2 (2015): 024006.
[223] Davidson et al., 2015.
[224] Davidson et al., 2015.
[225] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.
[226] Davidson et al., 2015.

number of the scenario they wish to observe into cell D5. Financial models are common practice when creating financial analysis for project development. The 11 scenarios are: Base, Upside Agreed-on Sale Price of kWh, Downside Agreed-on Sale Price of kWh, Upside PV Panel Output Capacity in Watts, Downside PV Panel Output Capacity in Watts, Upside Number of Panels in the Installation, Downside Number of Panels in the Installation, Upside Monthly kWh Use of the household, Downside Monthly kWh Use of the household, Upside Cost of the Entire Solar Installation, Downside Cost of the Entire Solar Installation.

Table 1: Data Table of Sensitivity Analysis from the P2P Financial Model

Sensitivity Analysis

Case #	Case Name	Sale Price per kWh	Consumption (kWh/month)	Number of Panels	Generation (kWh/month)	Total System Cost	Month Repaid	Day Repaid	Saved per Month vs. Utility
Active Case	BASE	$0.150	600	20	929.04	$ 11,700.00	4	130	$ 1,049.40
1	BASE	0.15	600	20	$ 929.04	$ 11,700.00	4	130	$ 1,049.40
2	Upside Price	*0.18*	600	20	$ 929.04	$ 11,700.00	4	108	$ 509.40
3	Downside Price	*0.12*	600	20	$ 929.04	$ 11,700.00	5	163	$ 1,589.40
4	Upside Panel W	0.15	600	*20*	*$ 1,161.30*	$ 11,700.00	4	130	$ 1,049.40
5	Downside Panel W	0.15	600	*20*	*$ 331.80*	$ 11,700.00	4	130	$ 1,049.40
6	Upside Panel #	0.15	600	*25*	$ 1,161.30	$ 11,700.00	4	130	$ 1,049.40
7	Downside Panel #	0.15	600	*14*	$ 650.33	$ 11,700.00	4	130	$ 1,049.40
8	Upside kWh Use	0.15	*800*	20	$ 929.04	$ 11,700.00	3	98	$ 1,399.20
9	Downside kWh Use	0.15	*500*	20	$ 929.04	$ 11,700.00	5	156	$ 874.50
10	Upside Cost	0.15	600	20	$ 929.04	*$ 20,000.00*	5	222	$ 1,049.40
11	Downside Cost	0.15	600	20	$ 929.04	*$ 7,000.00*	3	78	$ 1,049.40

This table displays the results of all scenarios from the P2P financial model. Only one variable changes in each scenario with the rest of the variables remaining at the BASE level. The changed variables are italicized.

The P2P Financial Model is a dynamic model that shows the resulting timeline of financing a solar project in Puerto Rico based on the many factors at play. Figure N(a) shows a screen picture of the dynamic financial model with Base as the Active Case. Table 1 displays the data table of results of the financial model in which the repayment schedule of a distributed solar network could operate under several different conditions. The first scenario, the Base, uses the average of the variables based on information acquired through interviews with Puerto Rican solar developers and through Puerto Rico-specific studies and reports. This model sets the agreed traded price of kWh at 15 ¢/kWh, a significant five cents per kWh under the Puerto Rican utilities cost. The base scenario numbers will hold for every other scenario except for one variable that will be examined in an upside case with a higher number and a downside case with a lower number. The variables examined are Sale Price per kWh (scenarios 2 & 3), Residential Consumption of kWh per month (8 & 9), Number of Panels in the Roof System (6 & 7), Power Output of Watts per Panel expressed in Table 1 as Generation of kWh per month (4 & 5), and the Total System Cost (10 & 11). The last three columns of Table 1 show the financial calculation results. Month Repaid in Table 1 shows the number of months after installation and operation that the system would be paid off based on the sale price per kWh and the total system cost. Day Repaid similarly shows the day after operation on which the system would be fully paid if conditions remained consistent. To navigate the scenario manager of the model, cell D5 can be manipulated to display one scenario's inputs and results throughout the entire model. Figures N(b), N(c), N(d), and N(e) depict closer looks at the cell style legend, the assumptions, the scenario manager, and the calculations.

Figure N(b): Cell Formatting Legend for the P2P Financial Model

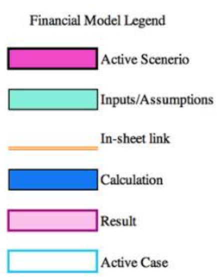


Figure N(c): Closer Image of the Inputs and Assumptions of the P2P Financial Model

	Inputs		Active Case
5	Active Scenerio	1	Active Case
6	Inputs	Units	BASE
8	Electricity Price		
9	PR's Avg Residential Price ($/kWh)	$ 0.2083	
10	Agreed Price for Solar ($/kWh)	$ 0.150	$ 0.150
12	Power Generation		
13	Number of Solar Panels on System	20	20
14	Sun Hours in PR (hours)	5.53	
15	Power Produced per Panel (W/panel)	280	280
16	Total Power Produced per Day (kWh/day)	30.968	
17	Total Power Produced per Month	929.04	
19	Power Consumption		
20	Average Power Consumed per Month (kWh)	600	600
21	Avg. Power Consumed per Day (kWh)	20	
23	Expense		
24	Cost per panel	$ 189.00	$ 120.00
25	Installation Cost ($/W)	$2	
26	Component Cost ($/W)	$5	
27	Total Installation Component Cost	$ 5,740.00	$ 4,360
28	Days per month	30	
29	Total System Cost (developers' estimate)	$ 17,000	$ 11,700

Figure N(d): Closer Image of Scenario Manager with all 11 Scenario Inputs of the P2P Financial Model

	G	H	I	J	K	L	M	N	O	P	Q	R
3		Scenerio Manager										
5	Case #	1	2	3	4	5	6	7	8	9	10	11
6	Name	BASE	Upside Price	Downside Price	Upside Panel W	Downside Panel W	Upside Panel #	Downside Panel #	Upside kWh Use	Downside kWh Use	Upside Cost	Downside Cost
10	Agreed Price $/kWh	$0.15	$0.18	$0.12	$0.15	$0.15	$0.15	$0.15	$0.15	$0.15	$0.15	$0.15
13	# Panels	20	20	20	20	20	25	14	20	20	20	20
15	W/panel	280	280	280	350	100	280	280	280	280	280	280
20	Monthly kWh Use	600	600	600	600	600	600	600	800	500	600	600
24	Price per Panel	$120.00	$120.00	$120.00	$199.00	$149.00	$120.00	$120.00	$120.00	$120.00	$120.00	$120.00
27	Installation cost	$4,360	$4,360	$4,360	$6,430	$3,680	$4,960	$3,640	$4,360	$4,360	$4,360	$4,360
29	Total system cost	$11,700	$11,700	$11,700	$11,700	$11,700	$11,700	$11,700	$11,700	$11,700	$20,000	$7,000

Figure N(e): Closer Image of the Scenario 1 Calculations from the P2P Financial Model

Row	A–C	D	E	F	G	H	I
31							
32	Calculations						
33							
34	Total Installation Cost	$ 11,700					
35	Total Power Produced per Day (kWh/day)	30.968					
36	Total Power Produced per Month (kWh/day)	929.04					
37							
38	Per day price of energy ($)	$ 90.00					
39	Per month price of energy ($)	$ 2,700.00					
40	Price Per Watt for Installation/Panel	$ 0.43					
41							
42	Time Period	0	1	2	3	4	5
43	Paying back Installation (month)		$ 9,000.0	$ 6,300.0	$ 3,600.0	$ 900.0	$ (1,800.0)
44	Absolute Value (month)		$ 9,000.0	$ 6,300.0	$ 3,600.0	$ 900.0	$ 1,800.0
45		900					
46			0	0	0	4	0
47	Month by which Installation repaid	4					
48							
49	Paying back Installation (day)		$ 11,610	$ 11,520	$ 11,430	$ 11,340	$ 11,250
50	Absolute Value of Pay		$ 11,610	$ 11,520	$ 11,430	$ 11,340	$ 11,250
51	Lowest ABS value	0					
52	Indicator for Final Year		0	0	0	0	0
53	Day by which Installation is repaid	130					
54							
55							
56							
57	Amount Paid Per Day for same kWh with a Utility		$ 124.98				
58	Amount Saved on Power Per Day by Using P2P		$ 34.98				
59							
60	Amount Paid Per Month for same kWh with a Utility		$ 3,749.40				
61	Amount Saved on Power Per Month by Using P2P		$ 1,049.40				
62	Per Year		$ 12,592.8				

This financial model uses a similar pay-per-kWh method used in PPAs, yet more advanced models could be made for other financing options. While currently 5-10% of solar projects are financed with upfront cash and the rest through 7-15 or maximum 20-year loans,[227,228] new avenues of project finance with minimal paperwork are available through smart contracts. Two financial options for independent solar developers to deploy that require no upfront payments from the client is to pay through electricity use or to pay through electricity sales to others. The pay-per-kWh-consumed version would measure the household's energy consumption and then automatically charge the prosumer and pay the developer for that electricity until the system was paid off. The sale price is what would be agreed upon between the developer and the homeowner. Table 1 shows that setting a price well below the utility price of electricity still pays back the developer in a few months since the developer essentially becomes a short-term energy supplier to the client. Once the system is entirely repaid, then the household owns their own system and can profit off selling excess electricity to neighbors. The second blockchain-based billing system could allow the prosumers to already consume their own generated electricity for free but use any profits received from sales to

[227] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.
[228] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

automatically pay back the developer. This option is riskier, as demand and consumption of one household is easier to predict than an entire P2P network. A financial model could also be drafted to reflect a hybrid of these options. What this model does not account for is any potential accrued interest developers may want to charge over time for unrepaid investments. Additionally, priority of electricity sale is a topic requiring more research and thought for each system in the event that multiple households are producing excess yet demand is limited and batteries are full.

Results from the sensitivity analysis in the financial model show that any system that installs solar and charges the consumer at a lower price from utilities will both be paid back in several months and save the prosumer an enormous amount by forgoing the expensive Puerto Rican utilities. This model is biased towards increased monthly consumption resulting in a faster repayment period. Even if the average monthly energy consumption reaches 500 kWh or 800 kWh when the average in Puerto Rico is 600 kWh,[229] the number of solar panels installed changes, or the cost of installation based on equipment or installation fees strays from the average $11,700[230] or $15,000,[231] then the system can be paid off within 3-5 months and save prosumers an average of $1,000 per month even while they are repaying the system [Table 1]. While this model can be heavily criticized for its assumptions, as it is not tailored to any specific blockchain solar system and does not differentiate between systems with or without energy storage options except in cost range, its dynamic ability to compare several scenarios at once provides valuable insight to outcomes despite changing variable.

An important consideration when developing a new financing system for developing solar power in Puerto Rico is maintenance and operation funding incorporation. Funding allocations for technology maintenance in an individual's finance choices and in larger sources of government

[229] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[230] Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.
[231] Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.

funding are necessary to keep up cleaning, repairs, and other services. Without this funding, then the operation of power generation facilities, whether small or utility scale, will deteriorate and put the island in a state of vulnerability similar to the 2017 hurricane season. Mr. Uriarte revealed another financial system improvement in his interview when asked what he saw as the best solution to the challenge of financing in Puerto Rico. He suggested to use funds from FEMA and other response organizations after the hurricanes to create solar loan insurance that would be similar to mortgage insurance. Solar insurance, he said, would make many creditors willing to lower their FICO score cut off, as financial institutions could feel covered by the insurance to take on more lending risk. Another use of the energy relief funds could be to lower prices of equipment, making overall project costs cheaper by several thousand dollars and thereby more accessible to residents. Developers like Mr. Uriarte and New Energy who are innovating and lobbying to find the best solutions for Puerto Rico are leading the island to a more stable, reliable, sustainable, and resilient economy, energy system, and society.

<u>Other Considerations and Conclusion</u>

Blockchain and distributed networks can transform entire energy systems and provide a new solution to systemic energy problems. Many challenges after the tragedy of hurricane destruction are ahead for Puerto Rico to rebuild a strong energy system that serves the people in ways that they understand and enjoy. Ledger technologies are difficult to understand and generating a real sense of trust in a network that claims to need no trust to operate is a difficult leap of faith for many people. In development work, many aspects can go wrong if they are not designed, built, and maintained by the people the project intends to help. Therefore, to overcome this barrier to make blockchain-based distributed solar networks viable in Puerto Rico, inclusion of homeowners in the process is necessary. This requires greater understanding and acceptance of the new technology. As Puerto

Rico aims to center itself in the heart of innovation with several start-up accelerator programs such as Parallel 18 gaining traction,[232] the incorporation of new technologies and companies is not in the distant future. A Puerto Rico Blockchain Community that meets once a month already exists, but they have yet to shift focus to the energy sector.[233]

A critical factor to examine of any new energy solution are the cost barriers to switching energy sources. Building new infrastructure is capital intensive, and Puerto Rico's government's debt presents a massive political challenge to funding an energy transition in the public sector. New models to finance solar installations can attract private investors and solar developers to bridge the financial gap. While government contracts awarded to developers like New Energy, WindMar, Maximo Solar, or other Puerto Rican companies are ideal, public-private partnerships do not always result in the intended benefits for people. Privatized investment, financing, project management, and construction will be necessary to rebuild Puerto Rico's energy system. However, both for reasons of individual skepticism and the potential for corporate avarice, a certain degree of caution surrounds entirely privatized systems. Encouraging private sector involvement in the development and sustainability of Puerto Rico's of the energy sector is regardless is an important next step.

Puerto Rico urgently needs a revitalization of energy stability in order to grow as a prosperous island. Renewable energy is the most important piece to this a resilient power system, as it provides independence from fossil fuels, reaps health co-benefits, minimizes environmental pollution, and provides a platform for innovation. Pairing renewable energy with a distributed connected system for peer-to-peer energy trading offers a system to cultivate more energy prosumers who own their own energy technology. Independence and autonomy are significant qualities for people living in areas with unreliable grids. The energy sector should not shy away from

[232] Parallel 18. "Home." *Parallel 18.* Accessed February 2019.
[233] Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

taking advantage of the benefits from new technologies. Improved transparency, cost-effectiveness, and efficiency are achieved through several solutions, but blockchain technology can provide all three to the energy sector. Blockchain is not yet the perfect ledger technology and must continue to be applied, measured, and assessed in order to fully understand its improvements and limitations. Global problems of natural disaster relief, energy sourcing, climate change, and environmental conservation all deserve dedicated research to find appropriate solutions, and innovation in technology is a valuable element to implementing solutions.

Bibliography

"About the Secretariat." UNFCCC. Accessed March 2019. https://unfccc.int/about-us/about-the-secretariat.

"About Us." Windmar PV. Accessed December 2018. http://www.windmarpv.com/.

Acevedo, Nicole. "Why Does Restoring Full Power in Puerto Rico Seem like a Never-ending Task?" *NBCNews.com*. February 19, 2018. Accessed March 2019. https://www.nbcnews.com/storyline/puerto-rico-crisis/why-does-restoring-full-power-puerto-rico-seem-never-ending-n847211.

"Air Pollution Sensors: Highlights from an EPA Workshop on the Evolution and Revolution in Low-Cost Participatory Air Monitoring." *EPA*. January 19, 2016. Accessed 2018. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=307254.

Amadeo, Kimberly. "Hurricane Harvey Shows How Climate Change Can Impact the Economy." *The Balance*. Accessed December 14, 2017. https://www.thebalance.com/hurricane-harvey-facts-damage-costs-4150087.

Asl-Soleimani, E., S. Farhangi, and M.s Zabihi. "The Effect of Tilt Angle, Air Pollution on Performance of Photovoltaic Systems in Tehran." *Renewable Energy* 24, no. 3-4 (2001): 459-68. doi:10.1016/s0960-1481(01)00029-5.

Autoridad De Energía Eléctrica. "Sistema Eléctrico." Quienes Somos Sistema Eléctrico. 2019. Accessed February 2019. https://aeepr.com/es-pr/quiénes-somos/sistema-electrico.

"Battery Backup for Puerto Rico's Grid Tied Solar Power Systems." Solar Power News & DIY Solar Tips. April 06, 2018. Accessed March 2019. https://www.altestore.com/blog/2018/01/battery-backup-puerto-rico-solar-power-systems/.

Bronder, Pascale. "Effective Disruption: How Blockchain Technology Can Transform the Energy Sector." LinkedIn. August 11, 2017. https://www.linkedin.com/pulse/effective-disruption-how-blockchain-technology-can-energy-bronder/.

Calderwood, Heather. "Puerto Rico - Tax Deduction for Solar Energy Systems." *DSIRE*. May 5, 2015. Accessed January 2019. http://programs.dsireusa.org/system/program/detail/181.

Champagne, A., Evansen, B., Heath, C., North, T. "Puerto Rico Residential Energy: Project Proposal submitted to the Puerto Rico Energy Affairs Administration." *PREPA*. (2010).

Chow, Judith C., and John G. Watson. "Review of PM2.5 and PM10 Apportionment for Fossil Fuel Combustion and Other Sources by the Chemical Mass Balance Receptor Model." *Energy & Fuels* 16, no. 2 (2002): 222-60. doi:10.1021/ef0101715.

Cordoba, Jose De. "Puerto Rico Tallies Up Devastation From Hurricane Maria." *The Wall Street Journal*. September 24, 2017. Accessed 2018. https://www.wsj.com/articles/puerto-rico-tallies-up-devastation-from-hurricane-maria-1506294520.

Council on Foreign Relations. "Distribution of blockchain initiatives in the electric power sector worldwide between March 2017 and March 2018, by application." *Statista - The Statistics Portal*. Retrieved March 8, 2019, from https://www.statista.com/statistics/866609/electricity-blockchain-initiatives-globally-by-application/.

Davidson, Carolyn, Daniel Steinberg, and Robert Margolis. "Exploring the Market for Third-party-owned Residential Photovoltaic Systems: Insights from Lease and Power-purchase Agreement Contract Structures and Costs in California." *Environmental Research Letters* 10, no. 2 (2015): 024006. doi:10.1088/1748-9326/10/2/024006.

Delucchi, Mark A., and Mark Z. Jacobson. "Providing All Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies." *Energy Policy* 39, no. 3 (2011): 1170-190. doi:10.1016/j.enpol.2010.11.045.

Di Matteo, Livio, and Di Matteo, Rosanna. "Evidence on the determinants of Canadian provincial government health expenditures: 1965–1991." *Journal of Health Economics* 17, no. 2 (1998):211-228. https://doi.org/10.1016/S0167-6296(97)00020-9.

Dincer, Ibrahim. "Renewable Energy and Sustainable Development: A Crucial Review." *Renewable and Sustainable Energy Reviews* 4, no. 2 (2000): 157-75. doi:10.1016/s1364-0321(99)00011-8.

"Distance Transmission." ScienceDirect Topics. Accessed March 2019. https://www.sciencedirect.com/topics/engineering/distance-transmission.

Dye, Timothy. "A Brief History of Air Quality Sensors." *TD Environmental*. 2018. Accessed 2019. http://tdenviro.com/.

"Energy 101: Algae-to-Fuel." Energy.gov. Accessed March 2019. https://www.energy.gov/eere/videos/energy-101-algae-fuel.

Eschner, Kat. "The Story of the Real Canary in the Coal Mine." *Smithsonian.com*. December 30, 2016. Accessed December 2018. https://www.smithsonianmag.com/smart-news/story-real-canary-coal-mine-180961570/.

Ezzati, Majid, and Daniel M. Kammen. "The Health Impacts of Exposure to Indoor Air Pollution from Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs." *Environmental Health Perspectives* 110, no. 11 (2002): 1057-068. doi:10.1289/ehp.021101057.

Farber, Daniel A. "Response and Recovery after Maria: Lessons for Disaster Law and Policy." *UC Berkeley*, June 19, 2018. doi:10.2139/ssrn.3174466.

Fares, Robert. "The Price of Solar Is Declining to Unprecedented Lows." *Scientific American*. August 27, 2016. Accessed February 2019. https://blogs.scientificamerican.com/plugged-in/the-price-of-solar-is-declining-to-unprecedented-lows/.

Fessenden, Ford, Robert Gebeloff, Mary Williams Walsh, and Troy Griggs. "Water Damage From Hurricane Harvey Extended Far Beyond Flood Zones." *The New York Times*. September 02, 2017. Accessed March 2019. https://www.nytimes.com/interactive/2017/09/01/us/houston-damaged-buildings-in-fema-flood-zones.html.

Fink, Sheri. "Nearly A Year After Hurricane Maria, Puerto Rico Revises Death Toll to 2,975." *The New York Times*. 28 August, 2018. https://www.nytimes.com/2018/08/28/us/puerto-rico-hurricane-maria-deaths.html.

Fritz, Angela. "Everything You Need to Know about Hurricane Irma." *The Washington Post*. September 20, 2017. Accessed 2019. https://www.washingtonpost.com/graphics/2017/national/hurricane-irma-updates/?noredirect=on&utm_term=.264e00949cd9.

Gbesemete, Kwame P., and Ulf-G. Gerdtham. "Determinants of Health Care Expenditure in Africa: A Cross-sectional Study." *World Development* 20, no. 2 (1992): 303-08. doi:10.1016/0305-750x(92)90108-8.

Geophysical Fluid Dynamics Laboratory. "Global Warming and Hurricanes." *National Oceanic and Atmospheric Administration*. Accessed April 2019. https://www.gfdl.noaa.gov/global-warming-and-hurricanes/.

George, Cindy, Margaret Kadifa, Lindsay Ellis, and Keri Blakinger. "Storm Deaths: Harvey Claims Lives of More than 75 in Texas." *Houston Chronicle*. October 09, 2017. Accessed 2018. http://www.chron.com/news/houston-weather/hurricaneharvey/article/Harvey-Aftermath-Houston-police-officer-dies-19-12159139.php.

"Goal 7: Sustainable Development Knowledge Platform." United Nations. Accessed January 2019. https://sustainabledevelopment.un.org/sdg7.

Gonzalez, Robbie. "The Monumental Task of Restoring Houston After Harvey." *Wired*. September 07, 2017. Accessed March 2019. https://www.wired.com/story/the-monumental-task-of-restoring-houston-after-harvey/.

Gonzalez, Victor. Interview by Pascale Bronder. Email Interview. January 31, 2019.

Gous, N., D. I. Boeras, B. Cheng, J. Takle, B. Cunningham and R. W. Peeling. "The impact of digital technologies on point-of-care diagnostics in resource-limited settings." *Expert Review of Molecular Diagnostics* 18, no. 4 (2018): 385-397.

Graham, David A. "Is the Federal Government Doing Enough for Puerto Rico?" *The Atlantic*. September 26, 2017. Accessed March 2019. https://www.theatlantic.com/politics/archive/2017/09/puerto-rico-hurricane-maria-relief-trump-federal/541122/.

Hansen, Paul, and Alan King. "The Determinants of Health Care Expenditure: A Cointegration Approach." *Journal of Health Economics* 15, no. 1 (1996): 127-37. doi:10.1016/0167-6296(95)00017-8.

Hansen, Annet C., and Harald K. Selte. "Air Pollution and Sick-leaves – is there a Connection? A Case Study using Air Pollution Data from Oslo." *Statistics Norway, Research Department* 197 (1997).

"Historic Disaster Response to Hurricane Harvey in Texas." Historic Disaster Response to Hurricane Harvey in Texas | FEMA.gov. September 22, 2017. Accessed 2018. https://www.fema.gov/news-release/2017/09/22/historic-disaster-response-hurricane-harvey-texas.

"How to Calculate Your Solar PV System - Maximo Solar." Accessed February 2019. http://greensolarpr.com/pdf/How to Calculate your Solar PV System.pdf.

"Hurricane Irene Slams Puerto Rico, Eyes U.S." *CBS News*. August 25, 2011. Accessed March 2019. https://www.cbsnews.com/news/hurricane-irene-slams-puerto-rico-eyes-us/.

"Hurricane Maria Is a Nightmare for Puerto Rico's Economy." *CNN Money*. September 25, 2017. Accessed October 2017. http://money.cnn.com/2017/09/25/news/economy/hurricane-maria-economic-damage/index.html.

Inglesi-Lotz, Roula, and Eyup Dogan. "The Role of Renewable versus Non-renewable Energy to the Level of CO2 Emissions a Panel Analysis of Sub- Saharan Africa's Big 10 Electricity Generators." Renewable Energy 123 (2018): 36-43. doi:10.1016/j.renene.2018.02.041.

Jerrett, M. "Environmental Influences on Healthcare Expenditures: An Exploratory Analysis from Ontario, Canada." *Journal of Epidemiology & Community Health* 57, no. 5 (2003): 334-38. doi:10.1136/jech.57.5.334.

Jervis, Rick. "'5 Months without Power': Blackout Is Latest Snag in Puerto Rico's Long Recovery from Hurricane Maria." USA Today. February 13, 2018. Accessed 2019. https://www.usatoday.com/story/news/2018/02/12/power-outage-puerto-rico-latest-snag-islands-long-recovery-hurricane-maria/329322002/.

Katsouyanni, K., A. Pantazopoulou, G. Touloumi, I. Tselepidaki, K. Moustris, D. Asimakopoulos, G. Poulopoulou, and D. Trichopoulos. "Evidence for Interaction between Air Pollution and High Temperature in the Causation of Excess Mortality." *Archives of Environmental Health: An International Journal* 48, no. 4 (1993): 235-42. doi:10.1080/00039896.1993.9940365.

Koken, Petra J M, Warren T. Piver, Frank Ye, Anne Elixhauser, Lola M. Olsen, and Christopher J. Portier. "Temperature, Air Pollution, and Hospitalization for Cardiovascular Diseases among Elderly People in Denver." *Environmental Health Perspectives* 111, no. 10 (2003): 1312-317. doi:10.1289/ehp.5957.

Kumar, A., Kumar, K., Kaushik, N., Sharma, S., and Saroj Mishra. "Renewable energy in India: Current status and future potentials." *Renewable and Sustainable Energy Reviews* 14, (2010): 2434-2442. doi:10.1016/j.rser.2010.04.003.

Landale, James. "What Is a Transformation Map?" *World Economic Forum*. November 8, 2017. Accessed December 2018. https://www.weforum.org/agenda/2017/11/what-is-a-transformation-map/.

"Lawsuit Filed before European Court of Justice against Inclusion of Forest Biomass in Renewable Energy Directive II." *Bernard Energy*. March 4, 2019. Accessed March 2019. http://bernardenergy.com/lastestdevelopments/lawsuit-filed-european-court-justice-inclusion-forest-biomass-renewable-energy-directive-ii/.

Lelieveld, J., J. S. Evans, M. Fnais, D. Giannadaki, and A. Pozzer. "The Contribution of Outdoor Air Pollution Sources to Premature Mortality on a Global Scale." *Nature* 525, no. 7569 (2015): 367-71. doi:10.1038/nature15371.

Lu, Denise, and Chris Alcantara. "Analysis | After Hurricane Maria, Puerto Rico Was in the Dark for 181 Days, 6 Hours and 45 Minutes." *The Washington Post*. April 4, 2018. Accessed February 2019. https://www.washingtonpost.com/graphics/2017/national/puerto-rico-hurricane-recovery/?utm_term=.8405de9c65e4.

Martinot, E., Chaurey. A., Lew, D., Moreira, J.R., Wamukonya, N. "Renewable Energy Markets in Developing Countries." *Annual Review of Energy and the Environment* 27, {2002}: 309-348. DOI: 10.1146/annurev.energy.27.122001.083444.

Matasci, Sara. "Solar Panel Cost: Avg. Solar Panel Prices by State in 2019 | EnergySage." Solar News. 2019. Accessed February 2019. https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/.

Maximo Solar Industries. "Maximo Solar Industries." *Maximosolar.com*. Accessed January 2019. https://www.maximosolar.com/en/.

"Metrics: Disability-Adjusted Life Year (DALY)." *World Health Organization*. March 11, 2014. Accessed April 09, 2019. https://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/.

Murthy, N. R. Vasudeva, and Victor Ukpolo. "Aggregate Health Care Expenditure in the United States: Evidence from Cointegration Tests." *Applied Economics* 26, no. 8 (1994): 797-802. doi:10.1080/00036849400000094.

Narayan, Paresh Kumar, and Seema Narayan. "Does Environmental Quality Influence Health Expenditures? Empirical Evidence from a Panel of Selected OECD Countries." *Ecological Economics* 65, no. 2 (2008): 367-74. doi:10.1016/j.ecolecon.2007.07.005.

Negra, N. Barberis, J. Todorovic, and T. Ackermann. "Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Wind Farms." *Electric Power Systems Research* 76, no. 11 (2006): 916-27. doi:10.1016/j.epsr.2005.11.004.

Nogot, Fatiha. Interview by Pascale Bronder. Personal Interview. December 31, 2019.

- Fatiha Nogot is a technical engineer at ACWA Power, the company who runs operation and maintenance at Morocco's 160 MW NOOR 1 Ouarzazate solar power plant.

O'Malley, Martin. "Resilient Rebuilding in Puerto Rico." *Rocky Mountain Institute*. May 30, 2018. Accessed March 2019. https://rmi.org/resilient-rebuilding-puerto-rico/.

OECD. "The Cost of Air Pollution - Health Impacts of Road Transport." *OECD*. May 21, 2014. http://www.oecd.org/env/the-cost-of-air-pollution-9789264210448-en.htm.

Office For Coastal Management. "Hurricane Costs." *National Oceanic and Atmospheric Administration*. Accessed March 2019. https://www.coast.noaa.gov/states/fast-facts/hurricane-costs.html.

"OpenSolar." Yale OpenLab. Accessed March 2019. https://openlab.yale.edu/open-solar.

"Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria." Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria | FEMA.gov. October 31, 2017. Accessed 2018. https://www.fema.gov/blog/2017-09-29/overview-federal-efforts-prepare-and-respond-hurricane-maria.

Parallel 18. "Home." Parallel 18. Accessed February 2019. https://parallel18.com/.

Parra, David, and Martin K. Patel. "The Nature of Combining Energy Storage Applications for Residential Battery Technology." *Applied Energy* 239 (2019): 1343-355. doi:10.1016/j.apenergy.2019.01.218.

Peck, Morgen E. "A Microgrid Grows in Brooklyn." *Scientific American*. April 22, 2016. Accessed August 2017. https://www.scientificamerican.com/article/a-microgrid-grows-in-brooklyn/.

Pope III, C. Arden, and Douglas W. Dockery. "Health Effects of Fine Particulate Air Pollution: Lines That Connect." *Journal of the Air & Waste Management Association* 56, no. 6 (2006): 707-08. doi:10.1080/10473289.2006.10464484.

"Public School Renewable Microgrid Opens in Orocovis." *Rocky Mountain Institute*. September 27, 2018. Accessed February 2019. https://rmi.org/press-release/public-school-renewable-microgrid-opens-in-orocovis/.

"Puerto Rico Power Fully Restored 18 Months After Hurricane Maria Wiped Out the Grid." *The Weather Channel*. March 21, 2019. Accessed March 2019. https://weather.com/news/news/2019-03-21-puerto-rico-power-restored-hurricane-maria.

PwC. "Industries seen as leaders in blockchain technology development worldwide as of 2018." *Statista - The Statistics Portal*. Retrieved March 22, 2019, from https://www.statista.com/statistics/920747/worldwide-blockchain-technology-development-leading-industries/.

Ravelohery N. Tahina. "Decentralization: Problems and Solutions - Madagascar Evidence." *Journal of Economics and Finance* 6, no. 2, (2015):1-9.

"Renewables Global Status Report." REN21. 2018. http://www.ren21.net/status-of-renewables/global-status-report/.

Reuters. "Kerry: Panel to Integrate Climate Threats into Foreign Policy Plans." *Business Insider*. November 10, 2015. Accessed March 2019. http://static1.businessinsider.com/r-kerry-panel-to-integrate-climate-threats-into-foreign-policy-plans-2015-11.

Robles, Frances, Kenan Davis, Sheri Fink, and Sarah Almukhtar. "Official Toll in Puerto Rico: 64. Actual Deaths May Be 1,052." *The New York Times*. December 08, 2017. Accessed December 12, 2017. https://www.nytimes.com/interactive/2017/12/08/us/puerto-rico-hurricane-maria-death-toll.html?emc=edit_nn_20171210&nl=morning-briefing&nlid=75970514&te=1&_r=0.

Safaricom. "M-PESA." Accessed 2017. https://www.safaricom.co.ke/personal/m-pesa.

Sengupta, Somini, and Charlotte De La Fuente. "Copenhagen Wants to Show How Cities Can Fight Climate Change." The New York Times. March 25, 2019. Accessed March 2019. https://www.nytimes.com/2019/03/25/climate/copenhagen-climate-change.html.

Smith, K. R. "Indoor Air Pollution in Developing Countries: Recommendations for Research." *Indoor Air* 12, no. 3 (2002): 198-207. doi:10.1034/j.1600-0668.2002.01137.x.

SolarWinds MSP. "Centralized Networks vs Decentralized Networks." *Solarwinds MSP*. November 28, 2018. Accessed February 2019. https://www.solarwindsmsp.com/blog/centralized-vs-decentralized-network.

Sowerwine, Charles. *France since 1870: Culture, Politics and Society*. London: Palgrave, 2018.

Spaen, Brian. "In 2 Years, Renewables Will Be Cheaper than Fossil Fuels." *World Economic Forum*. January 17, 2018. Accessed March 2019. https://www.weforum.org/agenda/2018/01/renewables-will-be-equal-or-cheaper-than-fossil-fuels-by-2020-according-to-research.

"Sulfur Dioxide Basics." EPA. June 28, 2018. https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#what%20is%20so2.

"The Paris Agreement Summary." *Climate Focus*. December 28, 2015. https://climatefocus.com/sites/default/files/20151228%20COP%2021%20briefing%20FIN.pdf

"The True Cost of Fossil Fuels: Saving on the Externalities of Pollution and Climate Change." *International Renewable Energy Agency*, 2016. https://irena.org/publications/2016/May/The-True-Cost-of-Fossil-Fuels-Saving-on-the-Externalities-of-Air-Pollution-and-Climate-Change.

Torres, Maximo. Interview by Pascale Bronder. Phone Interview. March 21, 2019.

Torres Placa, Tomás J., Roy Torbert, and Mike Henchen. "Collaborating for Puerto Rico's Energy Transformation." *Rocky Mountain Institute*. October 11, 2018. Accessed 2019. https://rmi.org/collaborating-for-puerto-ricos-energy-transformation/.

"Transformation Maps: Environment and Natural Resource Security." *World Economic Forum*. Accessed January 2019. https://toplink.weforum.org/knowledge/insight/a1Gb0000001hXikEAE/explore/dimension/a1Gb00000044D65EAE/summary.

Uriarte, Alejandro. Interview by Pascale Bronder. Phone Interview. March 26, 2019.

U.S. Census Bureau. "Puerto Rico: 2010 - Population and Housing Unit Counts - 2010 Census of Population and Housing." *U.S. Department of Commerce*. (2012).

U.S. Energy Information Administration. "EIA adds Puerto Rico data to its U.S. power plant inventory." *EIA*. July 9, 2018. Accessed December 2018. https://www.eia.gov/todayinenergy/detail.php?id=36613.

U.S. Energy Information Administration. "EIA electricity sales data for Puerto Rico show rate of recovery since hurricanes." *EIA*. August 6, 2018. Accessed December 2018. https://www.eia.gov/todayinenergy/detail.php?id=36832.

U.S. Energy Information Administration. "Most U.S. Utility-scale Solar Photovoltaic Power Plants Are 5 Megawatts or Smaller." February 7, 2019. Accessed March 2019. https://www.eia.gov/todayinenergy/detail.php?id=38272.

U.S. Energy Information Administration. "More than Half of Small-scale Photovoltaic Generation Comes from Residential Rooftops." *EIA Independent Statistics and Analysis*. June 1, 2017. Accessed 2018. https://www.eia.gov/todayinenergy/detail.php?id=31452.

U.S. Energy Information Administration. "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a Supplement to Form EIA-860): March 2018." December 2018. Accessed January 25, 2019. https://www.eia.gov/electricity/data/eia860/.

U.S. Energy Information Administration. "Preliminary Monthly Electric Generator Inventory (based on Form EIA-860M as a Supplement to Form EIA-860): November 2018." December 2018. Accessed January 25, 2019. https://www.eia.gov/electricity/data/eia860m/.

U.S. Energy Information Administration. "How Much Electricity Does an American Home Use?" EIA Independent Statistics and Analysis. October 26, 2018. Accessed March 2019. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3.

U.S. Energy Information Administration. "Puerto Rico: Territory Energy Profile Data." U.S. Energy Information Administration Independent Statistics and Analysis. March 21, 2019. Accessed March 2019. https://www.eia.gov/state/data.php?sid=RQ.

U.S. Energy Information Administration. "Monthly Form EIA-861M (formerly EIA-826) Detailed Data (1990 - Present)." EIA Electricity Data. March 26, 2019. Accessed March 26, 2019. https://www.eia.gov/electricity/data.php#sales.

U.S. Energy Information Administration. "Electric Power Monthly." EIA Independent Statistics and Analysis. March 26, 2019. Accessed March 2019. https://www.eia.gov/electricity/monthly/index.php.

"UN Supports Blockchain Technology for Climate Action." *UNFCCC*. January 22, 2018. Accessed January 2019. https://unfccc.int/news/un-supports-blockchain-technology-for-climate-action.

Vrana, Til Kristian, and Olve Mo. "Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables." *Energy Procedia* 94 (2016): 399-408. doi:10.1016/j.egypro.2016.09.202.

Webber, Tim. "What Does Being A U.S. Territory Mean For Puerto Rico?" *National Public Radio*. October 13, 2017. Accessed March 2019. https://www.npr.org/2017/10/13/557500279/what-does-being-a-u-s-territory-mean-for-puerto-rico.

World Bank. "Air Pollution Deaths Cost Global Economy US$225 Billion." *World Bank*. September 8, 2016. Accessed November 2018. http://www.worldbank.org/en/news/press-release/2016/09/08/air-pollution-deaths-cost-global-economy-225-billion.

World Health Organization. "Ambient (outdoor) Air Quality and Health." *World Health Organization*. May 2, 2018. Accessed December 2019. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

World Health Organization. "Air Pollution." *World Health Organization*. February 28, 2019. https://www.who.int/airpollution/en/.

World Health Organization "Deaths attributable to ambient air pollution (age standardized, per 100 000 population)." *World Health Organization*. 2016. http://gamapserver.who.int/mapLibrary/Files/Maps/Global_aap_deaths_age_standardized_per_capita_2016.png.

Yale University, and Expert Network. "Transformation Maps: Climate Change." *World Economic Forum*. Accessed January 2019. https://toplink.weforum.org/knowledge/insight/a1Gb0000000LHVfEAO/explore/summary.

Yee, Amy. "In Rural Bangladesh, Solar Power Dents Poverty." *The New York Times*. October 04, 2016. Accessed August 2017. https://www.nytimes.com/2016/10/04/opinion/in-rural-bangladesh-solar-power-dents-poverty.html?_r=0.

Zhang, Minsi, Yu Song, Xuhui Cai, and Jun Zhou. "Economic Assessment of the Health Effects Related to Particulate Matter Pollution in 111 Chinese Cities by Using Economic Burden of Disease Analysis." *Journal of Environmental Management* 88, no. 4 (2008): 947-54. doi:10.1016/j.jenvman.2007.04.019.

Zuidema, Thijs, and Andries Nentjes. "Health Damage of Air Pollution: An Estimate of a Dose-response Relationship for The Netherlands." *Air Pollution in the 21st Century - Priority Issues and Policy Studies in Environmental Science*, (1998): 981-1006. doi:10.1016/s0166-1116(98)80059-9.