The Longest Power Blackout in History and Energy Poverty

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Abstract

Hurricane María crossed Puerto Rico on September 20 of 2018 and caused a devastation that resulted in a power blackout that lasted 329 days and accumulated an estimate of Customer Hours of Lost Electricity Service (CHoLES) of more than 2.9 billion. While the length of the blackout is outstanding, more than 600 million people in the African Continent live without access to electricity. The analysis on the blackout has implications for the design on energy access solutions for remote rural communities in many African countries. One of the main results of this analysis is that almost a third of the total CHoLES was due to the last 200,000 customers that were reconnected to the grid from day 156 to day 329 after the Hurricane. With the lower cost of Solar PV + Battery Systems (PV+B), small solar rooftop systems provide a cost effective alternative to increase the resiliency from the bottom-up. An estimated capital investment of $1,400 million to install small PV+B systems in the last 200,000 homes reconnected would have reduced the blackout size by one third and the length of the blackout by 57%. Similarly, an investment of $3,500 million for the last 500,000 homes that were reconnected would have reduced the blackout size by two thirds and the length of the blackout by 78%. The decentralized nature of solar rooftop systems combined with the native generating power provides a strong case for the incorporation of the Appropriate Technology Framework in the transformation of the electric power system in Puerto Rico with the bottom-up grid concept. The main results provide important insights to deliver the required resilience at the lowest possible cost with a focus on decentralized resilience while also enabling a radically distributed power generation and energy storage system.

Keywords: Appropriate technology, customer hours of lost electric service, energy access, María, solar home systems

Paper category: Energy

INTRODUCTION

On September 20 Hurricane María crossed Puerto Rico and left a devastation that no other hurricane has done for the last 90 years. María was recorded as the strongest hurricane in the Atlantic during the last 60 years and the resulting impact is still being studied. For example, while the official deaths related to María was still 64, different studies suggested that the total number is much higher, 822 during September and October (Rivera and Rolke, 2018), 1,085 during September and October (Santos-Lozada and Howard, 2018) almost 3,000 between September and February (Santos-Burgoa et al. 2018) and even more than 4,000 from September 20 to December 31 2017 (Kishore, Marqués, Mahmud, et al. 2018).

The economic impact of María in Puerto Rico during 2017 has been studied with early estimates ranging from $16 to $20 billion (Estudios Técnicos, 2017). The total estimate of damages determined by the National Hurricane Center of the NOAA is $90 billion (NHC, 2018), which places María as the costliest hurricane on record to strike Puerto Rico and the US Virgin Islands, and the third costliest for all United States

including its colonial territories. Different aspects of recovery plans have been developed with the most recent one proposing a strategy that would take years to implement and an uncertain approach that focus on a disaster capitalism framework such as the highly centralized proposed recovery plan (COR3, 2018).

A recent report estimates that during the first year of emergency management and initial restorative efforts, more than 90% of the $5,000 million in federal aid that was spent was channeled through contractors outside of Puerto Rico limiting the multiplying effect that recovery efforts could have in the local economy (Lamba-Nieves and Santiago-Bartolomei, 2018). Furthermore, only 4% of the restoration funds is being proposed to improve health services. On the positive side, this includes a healthy amount of funds to enable most households to obtain a solar home system with batteries that could improve their resiliency. Household resiliency and the potential to build a grid from the bottom-up are two of the most important ramifications of this work and it has important energy policy implications.

The lack of power for an extended period of time in most communities has been a central factor in the large death toll, interruption to other services such as water and telecommunications, decreased safety in the roads, depressed economic activity, and higher cost of living in general. This paper explores the blackout in Puerto Rico starting with the total amount of Customer Hours of Lost Electricity Service (CHoLES) and an initial distribution of them among customers that: 1) recovered the service first, 2) those that did during after the first 10 weeks and 22 weeks, and 3) the customers that recovered service last. Access to good and reliable electricity is important to enable a good quality of life and the people of Puerto Rico experienced for 329 days, the longest blackout in history. These results place the María's Blackout as the longest in history and one of the largest blackouts ever recorded only second to the Hayan and Bopha typhoons (Houser & Marsters, 2018). Both typhoons produced massive power outages in a great portion of the Philippines, with a population of 100 million people, approximately 30 times the population of Puerto Rico.

The paper also takes a quick look at the potential impact that the blackout had in the number of deaths due to the hurricane. Another section provides short-term recommendations on how to better prevent such a massive blackout with a large toll on the lives of many people. A preliminary comparison is made between communities in Puerto Rico without power for an extended period of time, and communities that live without power in Africa. The last section focused on potential appropriate technology niche areas that could become increasingly important for communities in Puerto Rico and regions with high levels of energy poverty.

METHODOLOGY

This work is mainly based on publicly available data related to the blackout in Puerto Rico after Hurricane María. The main data used was collected from the U.S. Department of Energy Situation Reports from September 20 2017 to April 2018 (DOE, 2018). Additional data was collected from social media through official accounts of the Puerto Rico Electric Power Authority and the U.S. Army Corp of Engineers. The results presented here are the most comprehensive that have been made publicly available. To study the full extent of the impact that the longest blackout in history had in the people of Puerto Rico is outside of the scope of this work. However, the social impact of this power blackout, the inequities that it brought to light, and the search for ways forward to prevent such disasters are the main motivations of the study.

The electric power restoration data was used to estimate the total Customer Hours of Lost Electricity Service (CHoLES). A conservative estimate was determined as a lower bound for the total CHoLES substituting the percentage of customers without service with the information reported during the first 3 months after the Hurricane such as the percentage of normal peak load, percentage of historic average load, percentage of instant maximum load, and percentage of instant maximum production. The conservative estimate resulted in a total of 2,931 million CHoLES. A worst case scenario was also explored to establish an upper bound for the CHoLES even though the conservative estimate was used for the analysis. Other studies have placed the estimated CHoLES in 3,900 million by March 2018 (Román, 2018), 3,394 million by April 2018 (Houser & Marsters, 2018) and 3,316 million by May 2018 (Kwasinsky, Andrade, Castro-Sitiriche et al. 2018).

Table 1 shows that the total number of customers reported for September 2017 was 1,466,627 including 614 industrial customers, 123,702 commercial customers and 1,338,958 residential customers (PREPA, 2018). A worst case scenario was used to estimate the percentage of customers without power during the first 3 months. It is assumed that the industrial customers, with an average consumption of almost one thousand times more than residential, were reconnected to the power network first, followed by all the commercial customers. The industrial customers consumed between 12% and 14% of the total monthly energy from January to August in 2017, while it consumed between 9% and 18% from January to August in 2018. If 13% of usual generation is needed for industrial customers and assuming the worst case scenario in which all the industrial customers are served first, the first 26 days would be dedicated to the restoration of the 614 industrial customers. That would increase the total number of CHoLES in 6% for that period from 862 million to 915 million.

Table 1: Consumption PREPA Customers by Type

Customer Type	Number of Customers[1]	Customer Percentage	Energy Consumption Percentage[2]
Industrial	614	0.04%	13%
Commercial	123,702	8%	47%
Residential	1,338,958	91%	37%

The commercial customers consumed between 46% and 49% of the total monthly energy from January to August in 2017, while it consumed between 42% and 50% from January to August in 2018[3]. If 47% of usual generation is needed for commercial customers and assuming the worst case scenario in which all the commercial customers are served before the residential customers, the period from day 28 to day 70, November 29, would be dedicated to the restoration of the 123,702 commercial customers. That would increase the total number of CHoLES in 61% for that period, from 933 million to 1,504 million.

The residential customers consumed between 35% and 40% of the total monthly energy from January to August in 2017. If 37% of usual generation is needed for

[1] As of September 1, 2017.
[2] Using PREPA Data from January to August of 2017 and January to August of 2018.
[3] February was not included because it would represent only 6% of the consumption and it is most likely an error in the data.

residential customers and assuming the worst case scenario in which all the residential customers are served last, the period from day 71 to day 105 would be dedicated to the restoration of the 1,338,958 residential customers. That would increase the total number of CHoLES in 121% for that period from 398 million to 881 million. After Day 105, on January 3, 2018, the specific number of customers without service started to appear in DOE reports. In total, the worst case scenario resulted in 4,038 million CHoLES, or 1,107 million CHoLES more than the conservative estimate.

RESULTS AND DISCUSSION

The main work presented is based on the total customer hours of power outage, CHoLES. This type of index integrates the importance to prioritize blackouts for many customers, even if these are relatively short, and also considers the imperative to provide a viable alternative for remote rural communities that usually wait much more to recover access to electric power services. The results do not indicate that the last ones to be served should be the highly populated urban areas and it is probable that the restoration efforts will not drastically change. However, the results highlight the need to provide alternative energy options for those living in rural areas. Considering the transition phase the electric power industry in Puerto Rico is going through, it is crucial that the interests of those last customers in remote communities are put first when considering resilient distributed power systems.

One of the main results of this analysis is that almost a third of the total CHoLES (900 million) was due to the last 200,000 customers that were reconnected to the grid from day 156 to day 329 after the Hurricane. The estimates also indicate that slightly more than a third of the total CHoLES (1,041 million) were due to the 300,000 customers that were reconnected to the grid from day 71 to day 156 after the Hurricane. An estimate of 900 million CHoLES were due to the 967,000 customers that were reconnected to the grid from day 1 to day 71 after the Hurricane. Figure 1 shows how the total CHoLES were accumulated and the contribution that each of the three groups made to such a massive power outage.

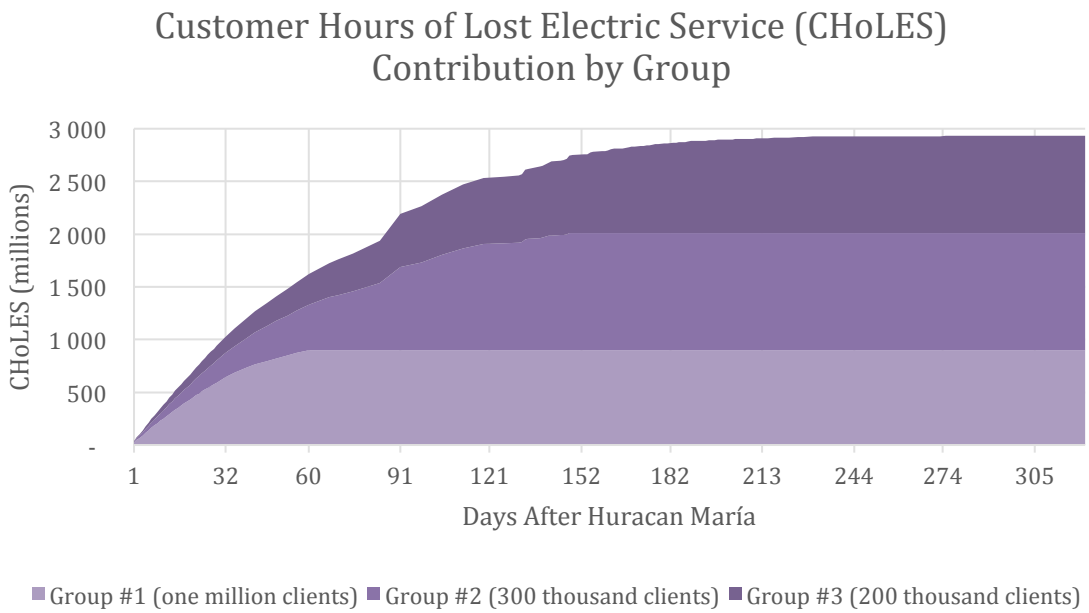

Figure 1: Customer Hours of Lost Electricity Service (CHoLES) by Group

Snapshot: Two months after Hurricane María

1. About one fourth of the seventy-eight municipalities had absolutely no electric power from PREPA. See municipalities in grey on Figure 2 by Status PR.
2. A fault on a 230 kV transmission line caused a decrease from 50% to 22% of the load that had been restored five days earlier, but it was back to 46% while 58.4% of the 1,146 transmission lines were functioning and 74.9% of the 344 substations were functioning (DOE, 2018).

Figure 2: Municipalities in Grey have 0% Electric Power on November 20 2017

Snapshot: Five months after Hurricane María,

1. Close to two hundred thousand households did not have power representing 13.4% of the total number of PREPA clients.
2. All Regions were electrified to a level of 80% or above except for the Caguas Region, which includes remote municipalities from the central mountain range such as Orocovis, but also those on the southwest coast that was hit hardest such as Yabucoa, Humacao and Naguabo as seen in Figure 3 from USACE.

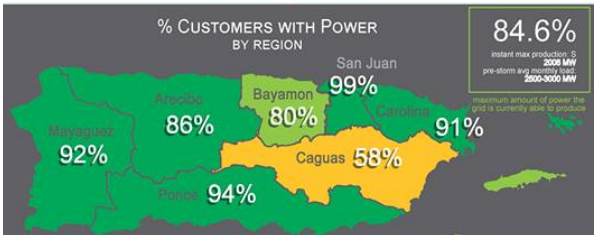

Figure 3: Power Restoration by Region on February 26 2018

Snapshot: Nine months after Hurricane María,

1. Fifteen thousand households did not have power representing 1% of the total number of PREPA clients.
2. The last 1% group contributed 83.6 million CHoLES in nine months without power. This is almost 3% of total 3 billion CHoLES and the equivalent of a national blackout more than 2 days (58 hours long) in Puerto Rico.
3. The last 1% to be electrified needs to become a priority for public policy in the recovery of Puerto Rico and the investments to make Puerto Rico more resilient.

Snapshot: Ten months after Hurricane María,

1. Five hundred households did not have power that accounted for 3.6 million CHoLES, which is the equivalent of a national blackout more than 2 hours long in Puerto Rico.
2. Nine municipalities were not energized 100%. Six of them, Utuado, Jayuya, Morovis, Adjuntas, Orocovis and Cayey, are in the central mountain region while the other three, Naguabo, Guayama and Guayanilla, are coastal municipalities that also have a large mountain rural area.

3. Two municipalities were less than 99% energized and they were both in the most remote central mountain region: Utuado and Jayuya.

Figure 4 and Figure 5 show the total restoration process of the electric power network in Puerto Rico and the recovery process by region, respectively. The regional data was only publicly available during the period that USACE reported it. The regional data shows that the Caguas region had a restoration curve much slower than the rest of the regions. The region of Arecibo was second in slower recovery for the first 145 days, then had a steep accent to move closer to the other regions. The slow recovery of Caguas and Arecibo is due to the fact that they contain most of the towns in the Central Mountain Range.

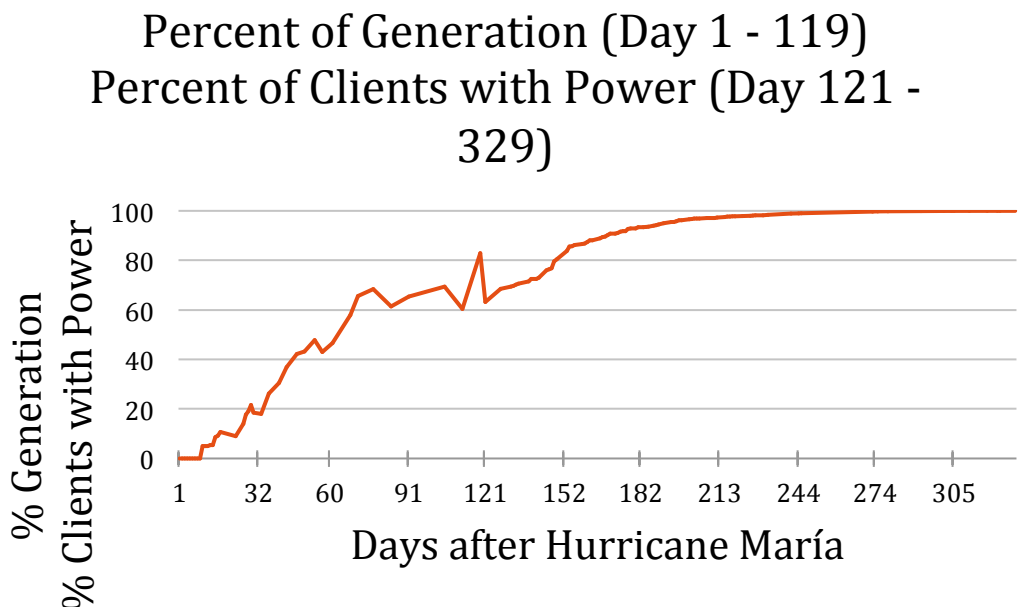

Figure 4. Snapshot to the Overall Power Recovery in Puerto Rico after Hurricane María

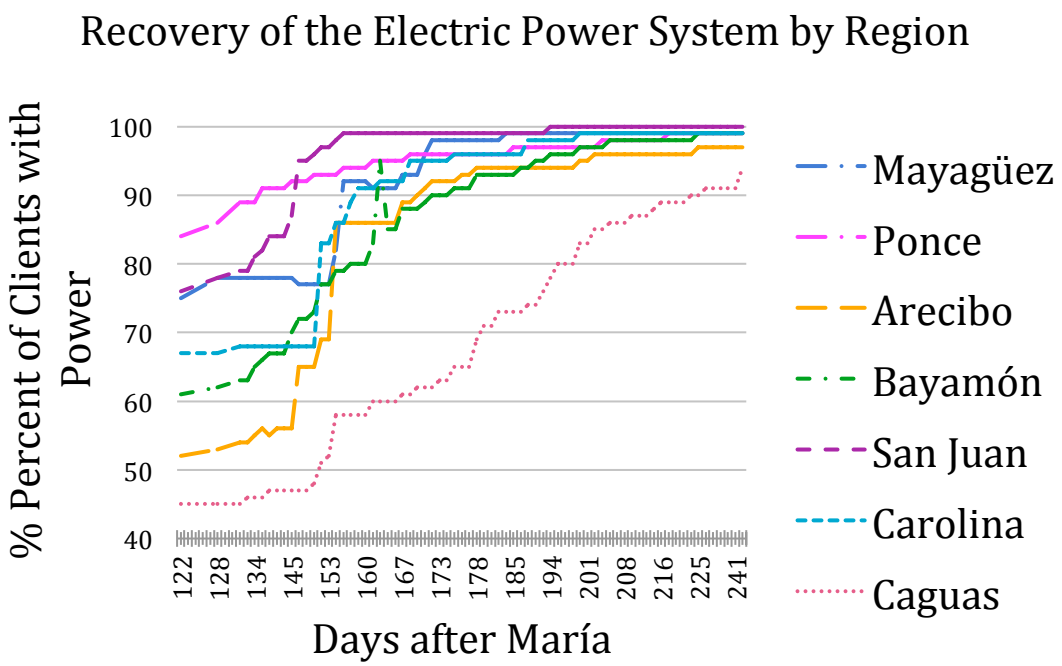

Figure 5. Regional Power Recovery in Puerto Rico after Hurricane María

Impact of Power Outage

While a comprehensive work to study the impact of the longest power outage in the people of Puerto Rico is needed, such study is outside of the scope of this effort. However, the studies focused on the deaths related to hurricane María provide a good idea of how critical is electric power to achieve a sustained quality of life. The Puerto Rico Center for Investigative Journalism (CPIPR) published their work that covers 487 cases from September 2017 to March 2018 (Sosa-Pascual, Campoy and Weissenstein, 2018), which are perhaps close to 25% of the total number of deaths related to Hurricane María. The larger group of causes of deaths reported by CPIPR was the one labelled due to "lack of electricity with 158 deaths which accounts for 32% of the cases. These 158 deaths include cases of in which there was no power for machines related to respiratory conditions, no refrigeration for insulin, bed sores due to electric bed not functioning, and accidents due to lack of appropriate lighting. It was also reported that "kidney-disease-related deaths rose nearly 43%, to 211" (Sosa-Pascual, Campoy and Weissenstein, 2018) because of the lack of appropriate power and enough water in dialysis centers.

A previous study based on a survey to 3,299 randomly chosen households across Puerto Rico reported that 83% of the households were without electricity in the most remote areas from September 20 to December 31 2017 (Kishore, Marqués, Mahmud, et al. 2018). The same study reported that, overall, households spent an average of 84 days without electricity, 68 days without water, and 41 days without mobile phone coverage for that period. However, considering that the power outage lasted a total of 314 days and that less than 60% of the households were connected to the grid by day 101 on December 31, the total average of days without electricity should now be much higher. A deeper look into the Appendix files with a focus on the proportional distribution of days without services ordered by remoteness and the tables with information of lack of access to medical care could be useful (Kishore, Marqués, Mahmud, et al. 2018b).

The study that estimated the number of deaths related to Hurricane María in 2,975 also determined that the estimated relative excess mortality was drastically higher for the lowest socioeconomic level with a relative excess ratio above 1.6 for January 2018 compared to values between 1.1 and 1.2 for the other two socioeconomic levels (Santos-Burgoa, et al. 2018). This is crucial information to appropriately setup a coherent energy policy that provides Puerto Ricans in the most vulnerable communities with the most resilient power sources and to improve their chances of survival. Even though Puerto Ricans went through the longest blackout in history, it needs to be put in context with other communities that lack universal access to electricity.

Long Term Power Outage and Energy Access

Perhaps the only communities that have experienced power outage longer than in Puerto Rico are the 1,000 million people that live without access to electricity every day, of which more than 500 million are in the African Continent, according to data from 2016 (IEA, 2017). Figure 6 shows the relationship between the approximate restoration service in Puerto Rico the first 40 days after Hurricane María and the electrification rate of different countries in Africa. Figure 7 shows the relationship between the approximate restoration service in Puerto Rico during the period consisting from day 40 to day 241 after Hurricane María and the electrification rate of different countries in Africa. Follow up studies need to analyse the impact of a power outage in life expectancy, life satisfaction and other dimensions that define the quality of life

compared to the effect that continued lack of access to power has on many communities in the African Continent. Available results provides evidence that decentralized solar PV plus battery systems could be the most appropriate solution to both, greatly improve the resilience of the Puerto Rican people and also enable universal electric energy access to the most remote communities in the African continent.

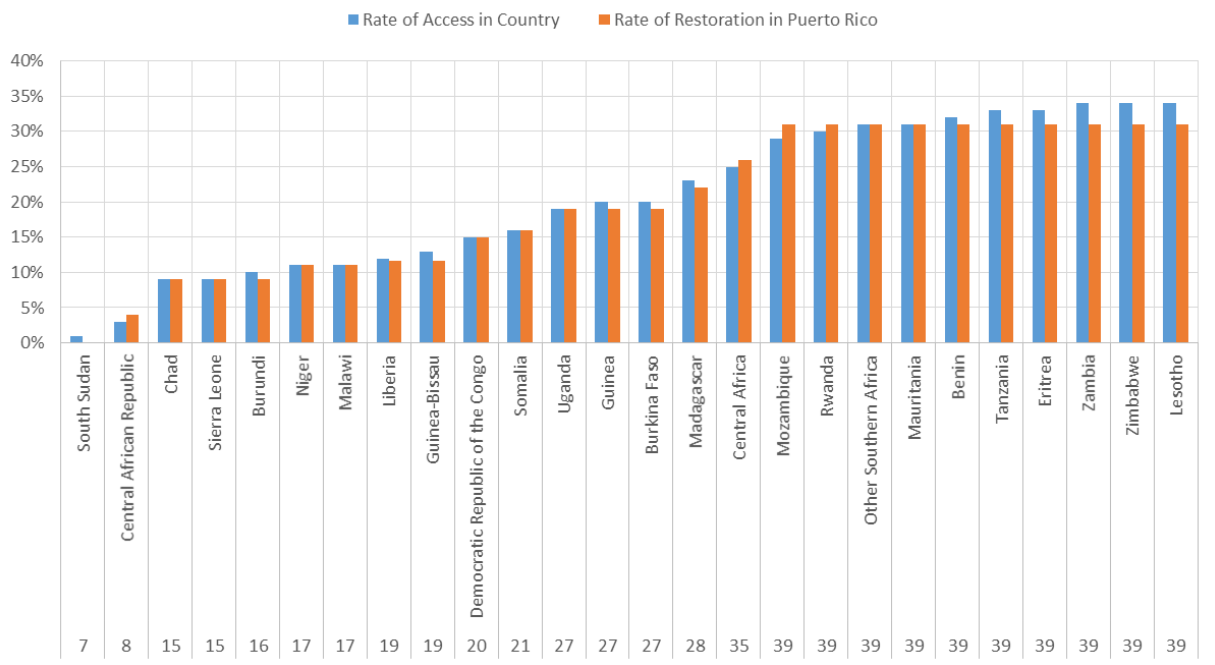

Figure 6: Comparison of Power Restoration in Puerto Rico during the First 40 Days and Electrification Rates in African Regions and Countries

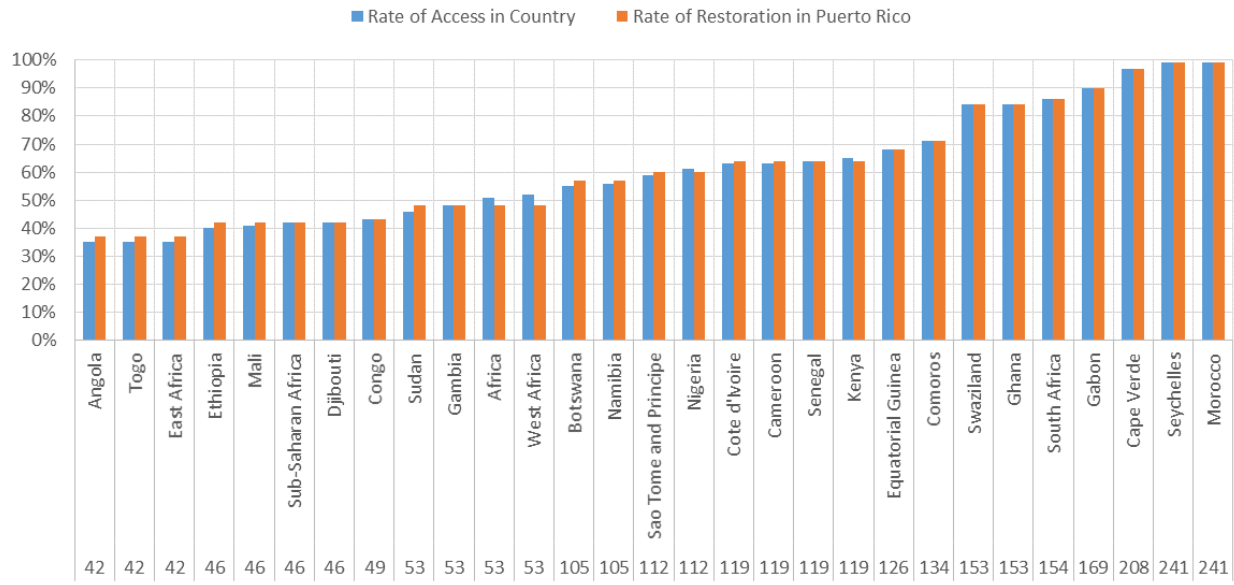

Figure 7: Comparison of Power Restoration in Puerto Rico from Day 40 to Day 241 after Hurricane María and Electrification Rates in African Regions and Countries

Revitalization Energy Policy for Puerto Rico

The status of the power recovery ten months after María tells us that the remote rural areas are the ones that need to be addressed first. The remote context calls for decentralized power solutions, which are mainly driven by solar PV plus battery systems (PV+B) at the household level. Other technologies will also play an important role to add levels of resiliency at community level and even at municipality and regional level. However, the radically distributed energy systems at household level should remain as the key building block for the resiliency at higher levels. For example, a community microgrid would benefit from a high level of penetration of rooftop solar home systems at household level, particularly if they also have energy storage capacity. The flexibility that a large amount of PV+B systems provide can enable a variety of smart grid capabilities in the future such as peer-to-peer energy transactions, variable electricity rate, demand side management, and virtual power plant.

One scenario is explored assuming 20% penetration of PV+B home systems in Puerto Rico before the peak of the 2020 hurricane season. Assume two hundred thousand houses with a minimum power generation capacity of 2 kW peak solar power and minimum energy storage of 10 kWh with an estimated installed system cost of $7,000 USD. In the medium and long term it is an underestimate because this cost is projected to decrease every year, mainly due to fast declining cost of energy storage and moderate decrease in solar PV cost. Further immediate savings could be achieved if communities get organized and purchase such systems in bloc.

The level of energy consumption that a small PV+B system can provide is aligned with the Responsible Wellbeing Framework with an approximate energy production close to 3,000 kWh annually. The recommended range of annual energy consumption per capita is between 400 kWh and 2,000 kWh, which could translate into 1,600 kWh to 8,000 kWh per household (Castro-Sitiriche and Jiménez-Rodríguez, 2014). If 200,000 PV+B minimum systems were installed by 2020, it would represent a total of 400 MW of PV generation capacity and 2 GWh of energy storage capacity radically distributed across the Puerto Rican archipelago at an estimated cost of $1,400 million.

In the 20% for 2020 scenario, special attention should be given to the communities that recovered electric power services last. If those 200,000 houses with the PV+B minimum systems belonged to those that recovered power last, the total CHoLES would have been 32% less, from 2,931 million CHoLES to 2,003 million CHoLES. Also, the total length of the longest blackout in history would have been about half long with a total of 156 days instead of 329. Also, this would imply an impressive 400 MW of PV generation capacity and an unprecedented 2 GWh of radically distributed energy storage capacity. To put this in context, the total residential energy storage capacity installed in 2017 was 29 MWh (SEPA, 2018) and it is projected to reach 774 MWh for 2018 (Maloney, 2018). The increase of residential energy storage installation capacity from 2017 to 2018 was 27 times more in only one year, which demonstrates that the market has the capacity to accommodate the drastic increase in demand that the proposed path for Puerto Rico would represent.

The families that spent more than five months without power should be given priority in the reconstruction phase that Puerto Rico is slowly starting. However, medium and long term recommendations are also relevant at this point in which PREPA is in a privatization process, the Fiscal Oversight and Management Board is controlling the process, and the long term planning for PREPA is taking place. A medium term energy policy goal of 500,000 households by 2025 with PV+B minimum systems is also included in the analysis. If those 500,000 houses with the PV+B minimum systems

belonged those that recovered power last, the total CHoLES would have been 69% less, from 2,931 million CHoLES to 912 million CHoLES. Also, the total length of the longest blackout in history would have been 71 days instead of 329.

A one million households with the PV+B minimum systems by 2035 is also included to support the vision of 50% energy consumption coming from renewable sources. One million of household PV+B minimum systems installed could contribute one-third of the 2035 goal of 50% energy from renewable energy sources. The cost estimate for one million households would be less than $7,000 million USD which is a reasonable investment level considering that the range from $4,200 to $6,200 USD earmarked for residential PV+B systems and an additional $26,000 million in energy investments in the Reconstruction Plan (COR3, 2018). When combined with the potential for business to also install solar rooftop PV+B systems and industrial customers to coordinate with utility scale PV+B systems the energy outlook for Puerto Rico emerges as a potential model for sustainable energy future worldwide. Table 2 provides the main numbers for the different future scenarios

Table 2. Minimum PV+B Projections for Puerto Rico Future Scenarios

year	2020	2025	2035
Percent of houses with minimum PV+B system	20%	50%	100%
Number of houses	200,000	500,000	1,000,000
PV Power Capacity (MW)	400	1,000	2,000
Percent of TOTAL Generation Capacity	8%	20%	40%
Energy Storage Capacity (GWh)	2	5	10
Estimate Annual PV Energy Generation (GWh)	584	1460	2920
Percent of Residential Annual Energy Consumption	8.98%	22.45%	44.89%
Percent of Total Annual Energy Consumption	3.37%	8.43%	16.87%

Appropriate Technology for Radical Decentralization of Power

A Solar PV + Battery Systems (PV+B), small solar rooftop systems, for example 2 kWp of PV and 10 kWh of storage at an estimate cost of $7,000 USD each, provide a cost effective alternative to increase the resiliency from the bottom-up. In the previous section the outlook for decentralized power in Puerto Rico demonstrated the feasibility for such a drastic change in direction. This kind of distributed approach has the potential to spark economic growth for many small solar businesses that can benefit from the installations of thousands of small solar PV+B systems. The prospects in remote rural African communities are very different because of the level of consumption, access to capital investments and household purchase power. However, the bottom-up resiliency concept and the bottom-up grid for Puerto Rico does provide a useful framework to build the energy future of remote rural communities in Africa with a completely decentralized structure.

Starting with modular PV+B at the household level with the potential to be expanded and the flexibility to be interconnected in nanogrids and microgrids in the near future, the following step would be to interconnect different networks at higher levels as it becomes economically feasible. Grid flexibility and flexible power converters will be central to future power networks. The potential for power aggregation and implementation of small smart systems will drive those remote communities to the forefront of power technology innovation. Enabling technologies such as smart meters,

flexible power converters, and novel concepts such as transactive energy and the internet of things, could become commonplace in the most remote places first. However, major investments in this technology and resources for pilot projects are needed before these technologies are effectively deployed in rural Africa. Puerto Rico could provide the bridge to connect the current innovations in decentralized power technologies and the market potential of more than 500 million people in the African continent living in energy poverty. The fact that small solar PV+B systems are needed in Puerto Rico and also in many African countries provides revitalization opportunities for remote rural communities and serve as a reminder that "small is beautiful".

CONCLUSIONS

The impact that the longest blackout in history had in the people of Puerto Rico was established from the people's perspective using the Customer hours of Lost Electricity Service (CHoLES). It was found that a small percentage of customers accounting for 14% of the PREPA customers contributed one third of the total CHoLES. A minimum PV+B system is proposed to provide Puerto Rican households with a much needed local resilience that can be built from the bottom-up. The level of energy consumption that a small PV+B system can provide is aligned with the Responsible Wellbeing Framework. Furthermore, the decentralized nature of solar rooftop systems combined with the native generating power provides a strong case for the incorporation of the Appropriate Technology Framework in the transformation of the electric power system in Puerto Rico with the bottom-up grid concept.

The bottom-up grid framework has the potential to transform the energy landscape of Puerto Rico and also the most remote communities in rural Africa. The main results provide important insights to deliver the required resilience at the lowest possible cost with a focus on decentralized resilience while also enabling a radically distributed power generation and energy storage. Future work is needed to further analyze the feasibility to transfer such a massive amounts of generation and storage capacity for energy access and their potential contribution to improve the quality of life of more than 500 million people. Similarly, much work needs to be done in the areas of flexible power converters and flexible grid capabilities, which are already positioned to play a major global role in the grid of the future.

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