Distributed energy system for resilient community

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Introduction

Climate change recently has caused several interruptions to human society. These events reveal vulnerabilities of the current urban systems. Water, energy and foods are examples to be kept supplied in the unfavorable events to sustain the urban systems. Energy is getting critical to serve the needs of human activities as society becomes complex. Reliability of energy supply has proven to be important especially during emergency situations where medical services are in high demand.

Decentralization of energy production and supply will play an important role to resilient community as it would be more robust in response to the disruptions. Community solar will be studied with respect to economic value and health benefit in response to outages due to disruptions. Installation of solar PV bears cost while it definitely incurs health benefit by keeping energy supply to those who need for their healthy needs. Monte Carlo simulation will be applied to address the uncertainty of conditions e.g., solar radiation, discount rate, energy cost change, etc. while Markov chain model would be used to estimate the change of health conditions and the benefit of an intervention of energy supply to the communities.

Impact of natural disasters on human health

Environmental changes from human activities are now incurring natural disasters associated with climate change. They include but are not limited to coastal storms, city heat waves, urban flooding and drought. Urbanization and environmental pollution are highly correlated and the proper management of resources and infrastructure planning seems missing in urban form until recently. As a result, people suffer from health issues due to the undesirable events including environmental pollution, which results from inappropriate natural resource management. Those challenges need to be discussed in terms of resilient and sustainable infrastructures to enhance community resilience.

Back in 2017, hurricane Maria left damages in Puerto Rico. The New York times (Robles et al. 2017) showed that additionally over 1,000 deaths for 2 months including the month when the disaster arrived on September 20, occurred in comparison to the past average deaths counts.

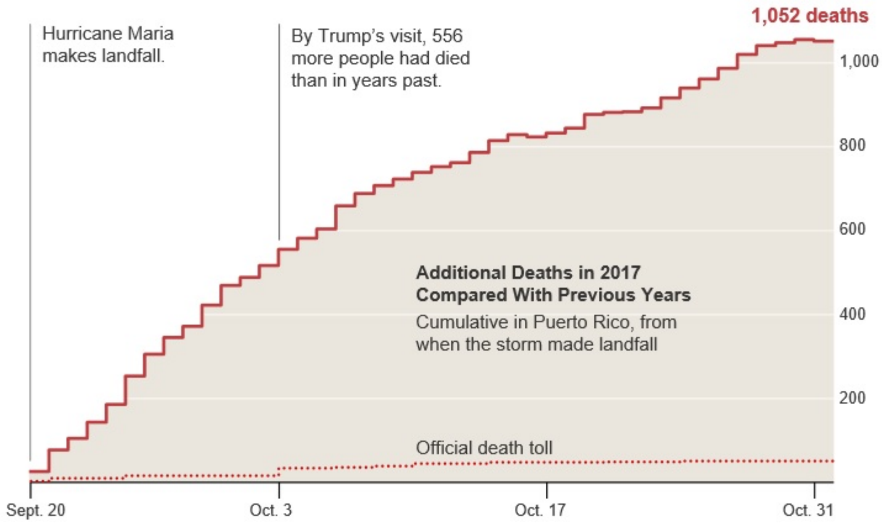

Figure 1: Additional deaths in Puerto Rico in 2017 (The New York Times)

This shows that the event most likely affects human health by increasing deaths noticeable compared to the amount of average deaths in the same period last 2 years. The deaths count is not limited to the direct impact from the hurricane but includes indirect influence of the event as well. It would be necessary to study what indirect factors caused the abnormal deaths. The fact that the trend of death seems getting closer to as usual at the end of October, the 2nd month after the hurricane Maria, confirms the natural disaster is somehow the main factor to this remarkable result of deaths.

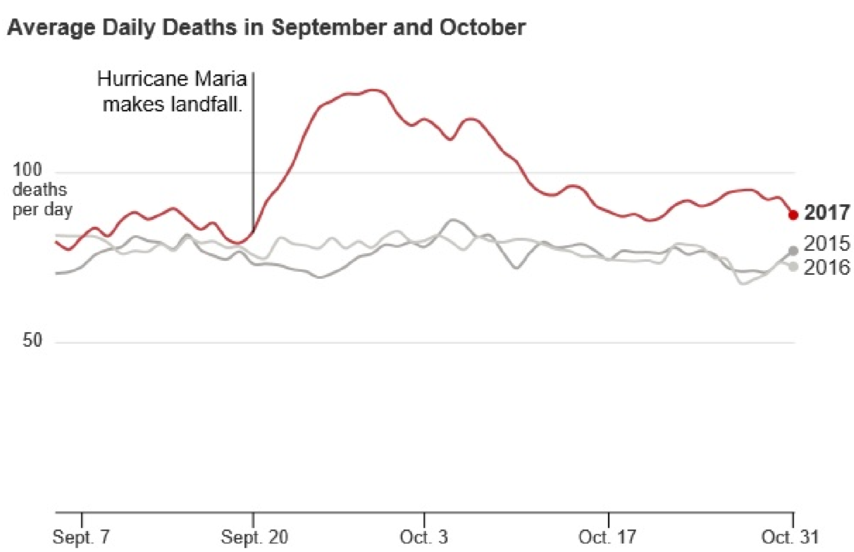

Figure 2: Average daily deaths for 2 months compared with last 2 years (The New York Times)

Average death in September past 2 years in Puerto Rico is about 645 for a group of respiratory diseases (i.e., Sepsis, Pnuemonia, and Emphysema), diabetes and Alzheimers. In comparison of the amount of deaths to the one in September, 2017 when the hurricane came, the 862 deaths is 217 more than the last 2 years average death in September. Especially respiratory diseases have higher increase changes, which is assumed to be related to electricity because respiratory patients need it to run their medical devices to get support of breathing. Diabetes patients are also sensitive to electricity because storing insulin needs to avoid heat to protect it's functionality.

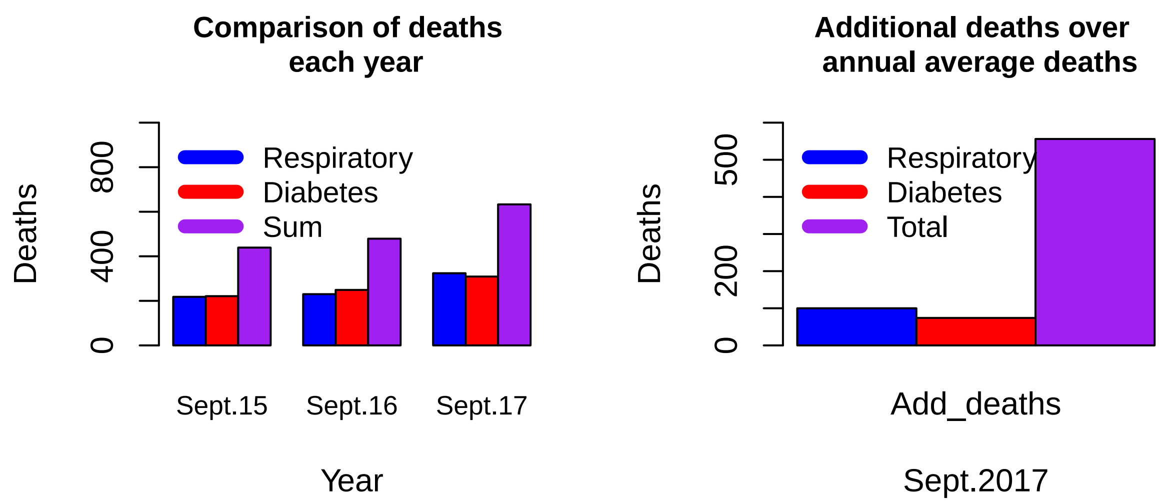

Figure 3: Noticeable deaths increases after the hurricane (Data:The New York Times)

174 additional deaths are from these respiratory diseases and diabetes (633 deaths in Sept 2017 as opposed to 439 deaths in Sept 2015). Given the additional 556 deaths during the 1st month of hurricane, 31.29% of the death regarding the disaster is attributed to the respiratory and diabetes deaths. At the same time this increased number of deaths, 174 is the same as 39.64% of the amount of deaths as usual.

Impact of energy supply on health

Electricity affects more on respiratory patients that mortality and respiratory hospital admissions increases significantly during blackout compared to those with cardiovascular and renal diseases (S. Lin et al. 2011). The Henry J. Kaiser Family Foundation (Michaud 2017) reported that 26 out of 65 hospitals (40%) were still running on emergency power supply such as fuel based generators disconnected to the regular grid by the middle of November, 2 months after the event. Assuming that the causes of deaths from respiratory and diabetes are from electricity blackout due the the damages by the hurricane, electricity could be considered to be the cause to the impact on deaths about 31.29% because respiratory and diabetes, out of 556 additional deaths, contribute 174 deaths.

Causes of death	Sept. 2015	Sept. 2016	Sept. 2017	Pct. change
Sepsis	64	61	92	+47
Pneumonia	50	55	76	+45
Emphysema and other breathing disorders	104	114	156	+43
Diabetes	221	249	309	+31
Alzheimer's and Parkinson's	189	183	229	+23

Figure 4: Causes of death based on a month, September (The New York Times)

About 517 in thousands or 15% of 3.5 million Puerto Ricans are diabetics and about 2,800 people die annually due to the disease. Given this abnormal situation, the hurricane interrupted the trend by increasing the number of death, about 150 more people died due to diabetes (estimated with the data). Markov chain transition probability could be constructed to figure out the impact of an interruption of power supply by means of distributed energy system such as solar PV on cost and effectiveness of it. Since diabetes are attributed to about 42% of additional deaths related to electricity due to the disaster (assuming all additional deaths from diabetes and respiratory diseases are from lack of electricity), the impact of introducing distributed energy system (DES) on human health can be addressed by adding the rest of 58% proportionally to the 42% weight.

Markov model for CEA

Cost effectiveness analysis (CEA) using Markov model would help to see an impact of intervesion of treatment to a system. In a normal condition in Puerto Rico, with the fact that diabetics seldom completely recover, about the portion of 0.01317 diabetics dies ("Number of Diabetes Deaths Per 100,000 Population" 2018); average probability to become diabetics is 0.00232 (Joslin 2018); and annual deaths is about 29,500 (0.0089 of total Puerto Rican population), transition prabability matrix is:

Table 1: Transition Matrix (normal)

	nodiabetes	diabetes	death
nodiabetes	0.98949	0.00232	0.00819
diabetes	0.00000	0.98683	0.01317
death	0.00000	0.00000	1.00000

Hurricane changes the transition probability such that about 1,000 deaths are added and about 150 deaths out of the 1,000 deaths are due to the diabetes. Accordingly, a transition prabability in the interrupted situation is:

Table 2: Transition Matrix (interruption)

	nodiabetes	diabetes	death
nodiabetes	0.9891845	0.00232	0.0084955
diabetes	0.0000000	0.98650	0.0135000
death	0.0000000	0.00000	1.0000000

Unexpected events such as hurricanes are assumed to occur with 10% probability (i.e. once 10 years). This prior probability could be changed to lower or higher value given data collection, or experienced information such that posterior probability is kept updated. Since this study will have the time window of 20 years, interrupted transition probability and normal transition one will be combined with an assumption of 10% probability of interruption.

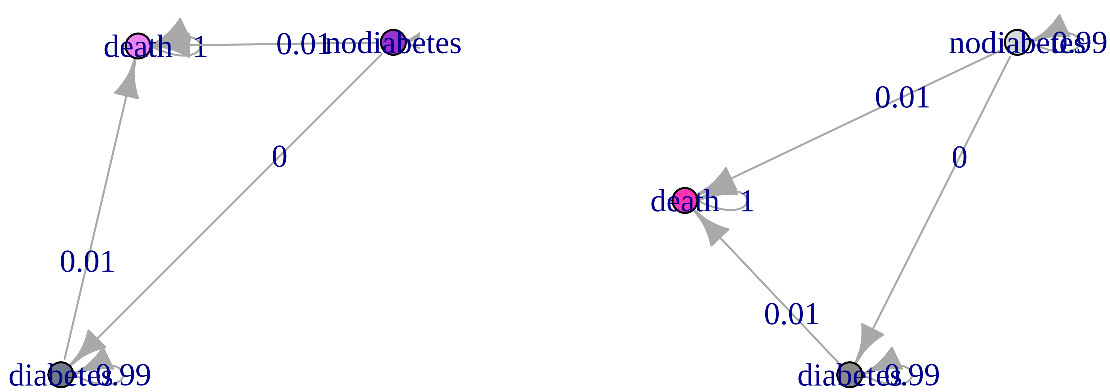

Figure 5: Markov chain for normal and interruption

According to American Diabetes (AmericanDiabetesAssociation 2018), annually $327 billion is spent for 30 million diabetics that $10,900 per one diabetic is approximately estimated. USA public expenditure (excluding private) for health per capita is about $4,800 in 2016 (OECD 2018). Assuming there is not much change in the value in 2017, the cost analysis can be performed based these cost estimation for 20 years scenario. Utility score for non-Asian, non-Hispanic with annual house income of more than $40,000 and without diabetes complications is 0.92 and for those other than them would be 0.80 (Zhang et al. 2012). In this regard, considering the socio-economic and demographic characteristics in Puerto Rico, a utility score of 0.80 for diabetes is chosen for this analysis. Normal scenario (i.e. there is no chance that unexpected events such as hurricane, happens) shows that discounted QALY and discounted cost are getting lower. Interruption scenario which is assumed with 10% increase in health cost with 10% probability of getting the disaster (probably twice in 20 years), shows a similar pattern but a bit slight difference.

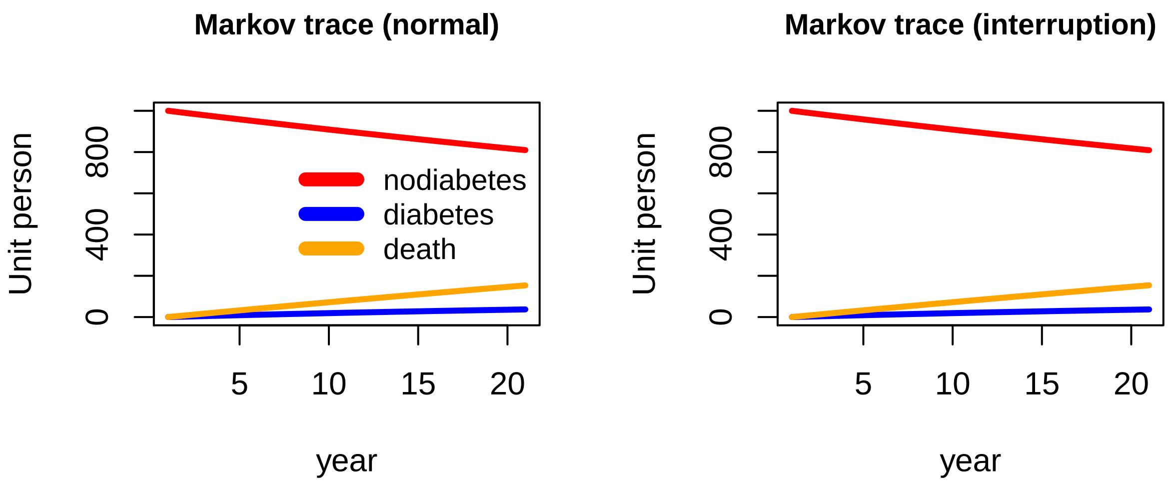

Figure 6: Markov trace for normal and interruption

Cost effectiveness ratio such as incremental cost effectiveness ratio (ICER) can present the effectiveness of treatment or changes to the system. Given unit benefit or QALY, how much cost is required for the treatment to the system change will be calculated as below:

$$\frac{Cost_{treated} - Cost_{untreated}}{Benefit_{treated} - Benefit_{untreated}} = ICER = -7.489883 \times 10^4 USD/QALY$$

Since disaster causes increase in cost and decrease in QALY, the ICER, 74.9 thousand dollars is considered to be benefit rather than cost. This means that by supplying uninterrupted power supply to the diabetes patients, the situation would remain the normal condition without the interruption from the undesirable events, thus the value of 74.9 thousand dollars per an unit QALY would be obtained. For the simulated 20 years, the scenario with 10% probability of disasters has 1,723 more deaths, $676.7 million more cost, and 9,042 less QALY. It is assumed that by supplying uninterrupted power supply, the gap of higher deaths, cost and lower QALY would decrease.

Table 3: Cost-Effectiveness of discounted QALY and cost

	d.qaly	t.cost
Normal	11651.72	57345362
Intervention	11648.98	57550435

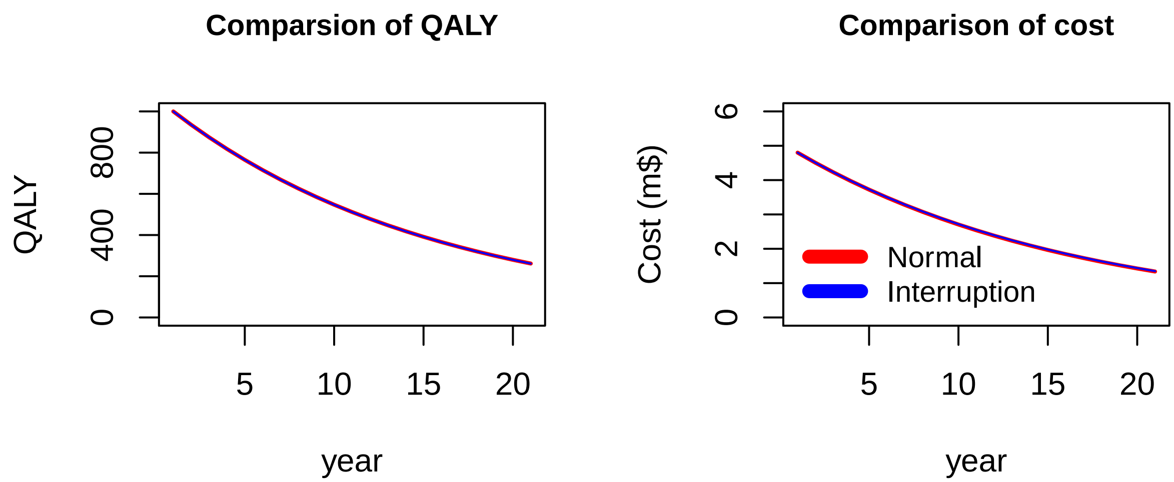

Figure 7: Comparion of the 2 scenarios for QALY and health cost

How much would it cost to have uninterrupted power supplies to those in need during the hardships? For the sake of simple analyses, it is assumed that all the hospitals in Puerto Rico are accessible by all the citizens for a short time and solar PV system on roof of each hospital can serve uninterrupted power supply to the local people even during the undesirable events. Considering there are 65 hospitals in Puerto Rico, it would be necessary to estimate upfront cost and break even period of installation of DES to hospitals. One hospital approximately deals with 1.14 deaths in the month when the event happened and the 74 additional deaths of diabetics occurring in the month when the disaster landed. With the fact that respiratory patients are 58% and diabetics are 42% covering the additional deaths which is assumed to be due to the lack of electricity, one hospital would take about additional 2.7 deaths occurring during the month of the disaster.

PV system configuration in a hospital

One hospital, Puerto Rico hospital San Gerardo was chosen for this study. The area of roof of Puerto Rico hospital San Gerardo where the designed PV system will sit on is estimated 2,675 square meter.

Figure 8: Roof area of Puetro rico Hospital San Gerardo

Solar panels were chosen mainly based on the estimated capacity and efficiency. A model with 320W, 19% efficiency (i.e., platinum) and the size of 1640 x 1000 x 40 was selected because most of common solar panels in the market are from 250W to 320W and approximately around 5.4ft x 3ft or 1.64m x 1m (In case of 60 cells). Solar panel size is related to weights, and regulations and the related market tends to standardize size and capacity of solar panels (PowerScout 2018). Array type for the PV installation was assumed to be fixed open rack, which means the panel direction and degree of tilt will be fixed permanently once installed on the site.

Table 4: PV System configuration for PV *

Description	Value
Lat (deg N):	18.05
Long (deg W):	66.62
DC System Size (kW):	508.3
Module Type:	Premium
Array Type:	Fixed (open rack)
Array Tilt (deg):	20
Array Azimuth (deg):	180
System Losses:	14.08
Invert Efficiency:	96
DC to AC Size Ratio:	1.2
Average Cost of Electricity Purchased from Utility ($/kWh):	0.225
Capacity Factor (%)	17.4

* Source: NREL, http://pvwatts.nrel.gov/pvwatts.php

Through the PVwatts calculator estimation (http://pvwatts.nrel.gov/pvwatts.php), the PV capacity is estimated to 508.3 kW in DC which is converted to 609.96 kW in AC with the assumption of 1.2 ratio considering the weather condition and the characteristics of the roof of the hospital (i.e., roof area, no shadow, pain, 180 degree of azimuth, and 20 degree of tilt).

Table 5: Estimated variables for simulation *

	Value
Area(sqm)	2675.000
Capacity(kWAC)	609.960
Install cost($/watt)	3.380
Total cost(k$)	2061.665
Avg.elec.cost($/kWh)	0.225
Annual discount rate	0.060

* Solar-Estimate, Solar calculator, https://www.solar-estimate.org/

Installation cost (i.e. cost per watt, $/watt) including purchase of panel, labor cost, or any administration work, are set based on state in the US. This is because it is hard to compare the cost of installation depending upon the different characteristics of installation environment such as different home size, PV system and labor cost. By introducing installation cost per watt, the upfront cost is roughly estimated regardless of the differences. In case of Puerto Rico, the installation cost is approximately $3.38/watt. Total installation cost is accordingly estimated to $2061.66 in thousands for 508.3 kW DC PV system. This upfront cost could be adjusted with government incentives or tax credits if applicable. Average cost of electricity in Puerto Rico is recently (Dec. 2017) $0.225/ kWh according to US Energy Information Administration (eia 2018). This value will be used to analyze the designed PV system in this study.

Monte Carlo simulation for NPV and DPP

AC energy produced through the PV system is estimated 773,790 kWh per year. These estimated values are set as a baseline to compare with probabilistic analysis. AC energy production and electricity cost rate every year are uncertain such that there are always worse or better scenarios in the prediction. That being said, these variables were set with a uniform distribution with extreme boundaries (i.e. minimum and maximum). Average rate increase for the cost of electricity is 8% according to the historical trend. Annual maintenance cost for solar PV system is set to $7.5/kW (Vella 2016).

A simulation model was developed based on 20 years with interest rate of 6%. To figure out the system performance, Net Present Value (NPV) and Discounted Payback Periods (DPP) were estimated with the 100 times of run of Monte Carlo simulation.

Table 6: Estimation of electricity generation*

Month	AC System Output(kWh)	Solar Radiation (kWh/m^2/day)	Plane of Array Irradiance (W/m^2)	DC array Output (kWh)	Value ($)
1	65134.28	5.35	165.86	67906.08	14,642.19
2	62801.10	5.78	161.70	65453.79	14,117.69
3	70190.34	5.78	179.21	73173.96	15,778.79
4	64682.86	5.58	167.28	67554.09	14,540.71
5	63301.67	5.26	163.00	66115.14	14,230.22
6	62131.98	5.27	158.08	64864.30	13,967.27
7	67817.48	5.60	173.66	70777.88	15,245.37
8	65064.41	5.42	167.90	67956.07	14,626.48
9	64051.39	5.48	164.27	66844.64	14,398.75
10	63160.16	5.27	163.40	65924.01	14,198.40
11	61077.93	5.21	156.30	63694.29	13,730.32
12	64376.89	5.31	164.49	67147.05	14,471.93
Total	773790.50	65.29	1985.15	807411.30	173948.12

* Source: NREL, http://pvwatts.nrel.gov/pvwatts.php

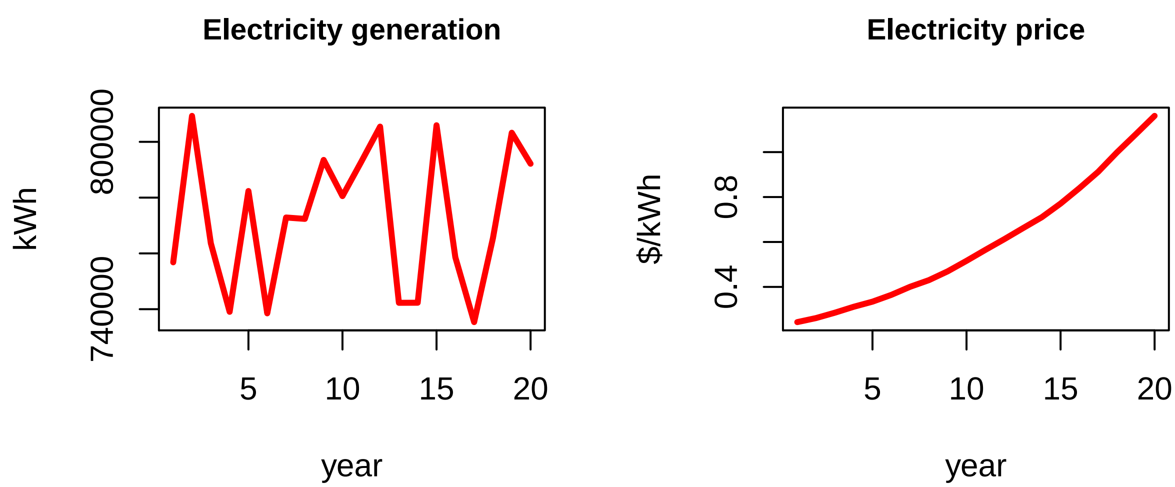

Figure 9: Annual electricity generation and cost estimation (1 simulation)

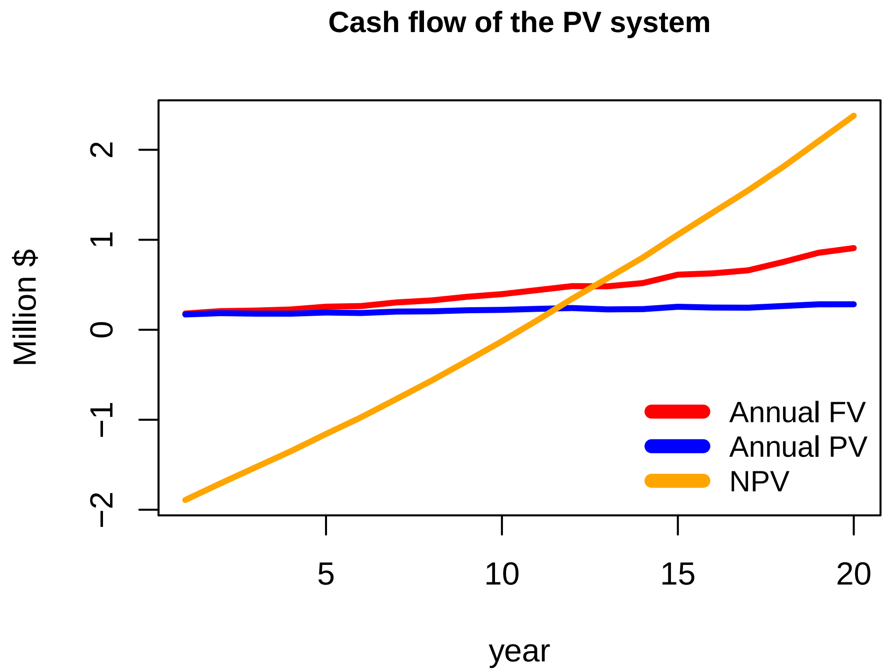

Figure 10: Cash flow and NPV from electricity generation

Average NPV is \$2.37 in millions with 0.1 x 10^6 standard deviation and average DPP is 10.48 years with 0.18 standard deviation. With 90% confidence interval, NPV is between \$2.36 in millions and \$2.39 in millions. DPP is between 10.45 years and 10.51 years. This means net present value for 20 years is highly profitable and within 11 years, the upfront cost could be paid off. This shows installation PV in Puerto Rico has higher NPV and lower DPP. This is mainly because the electricity price in Puerto Rico is higher than any other states such that saving electricity expedites the DPP and higher NPV.

Table 7: Average NPV and DPP

	Mean	CI 90%-	CI 90%+
NPV	2374401.58	2357355.54	2391447.63
DPP	10.48	10.45	10.51

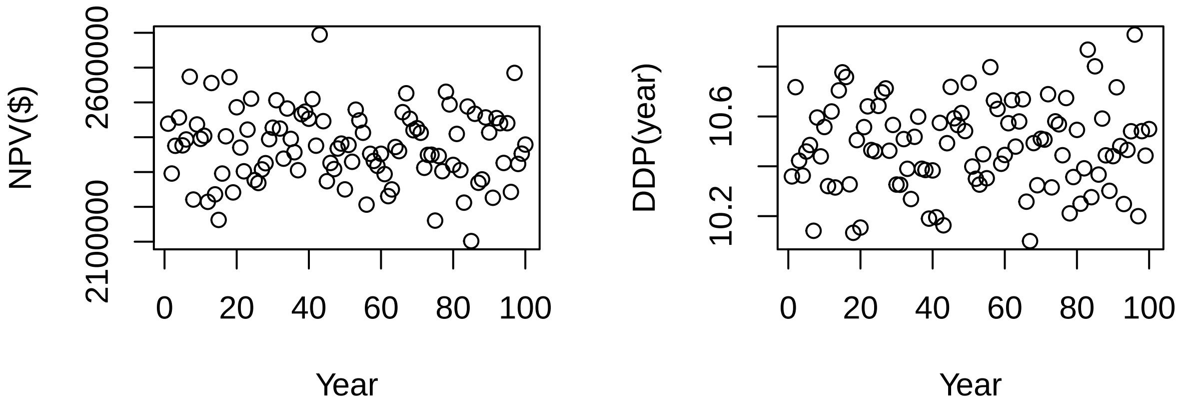

Figure 11: Simulation of 100 times for NPV and DPP

PV system effectiveness including health benefit

Having PV system has economic value as it generates electricity, but also it has a positive impact on health during unexpected events. Health impact on diabetes was caculated with Markov model with cost and QALY in the previous analysis. Inculding this economic value of health benefit from having PV system, would expedite the DPP such that the upfront cost to invest money for the PV system would be paid off earlier and increase NPV during the 20 years time window. Considering the weight portion of diabetes and respiratory diseases (42% of diabetes and 58% of respiratory diseases), annual estimated health benefits are assumed to be 2.38 times of the health benefit of diabetes. After 100 simulations of cash flow of PV investment including health benefit, it turns out that average NPV is about $2.8 million and average DPP is about 9.7 years.

Table 8: Average NPV and DPP

	Mean	CI 90%-	CI 90%+
NPV	2837912.35	2821714.66	2854110.04
DPP	9.67	9.65	9.69

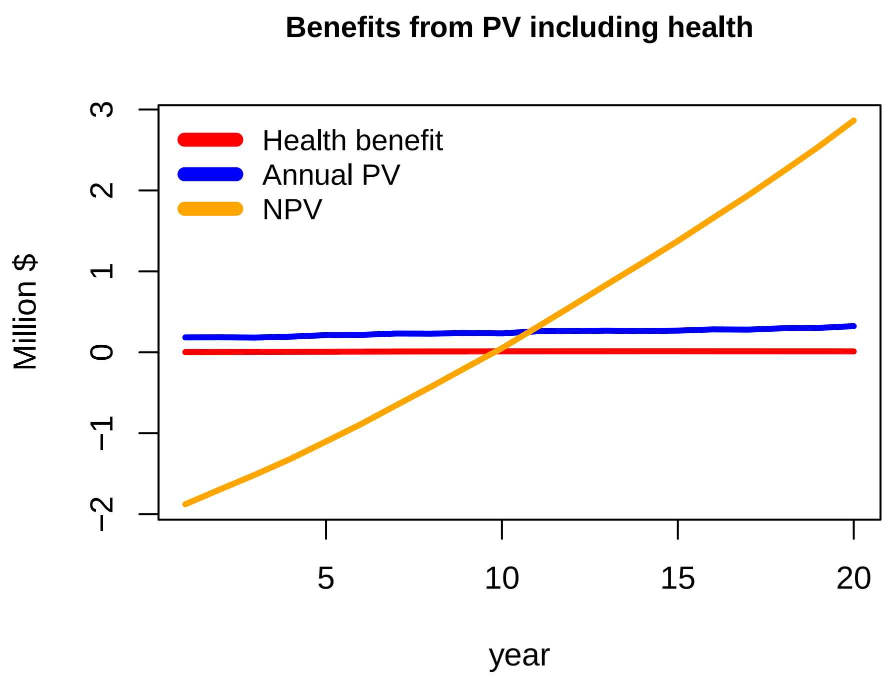

Figure 12: Electricity NPV with health benefit

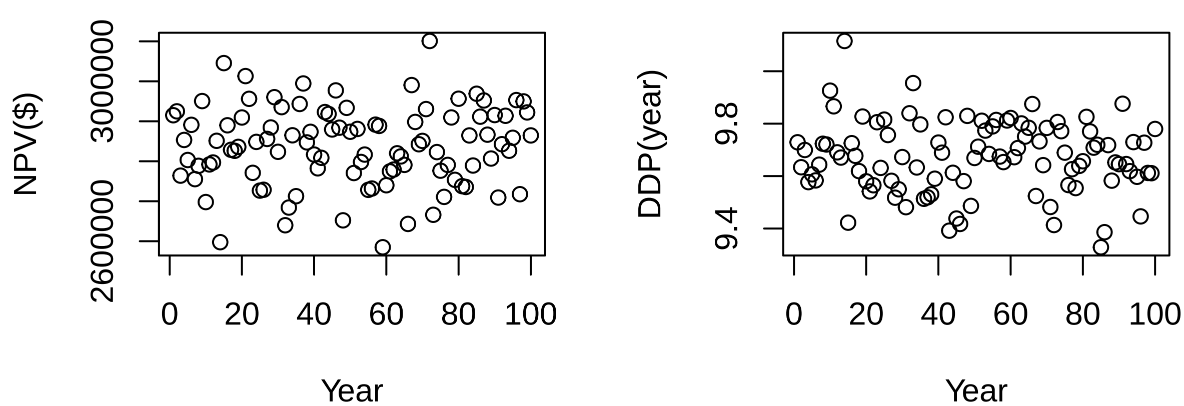

Figure 13: Simulation of 100 times for NPV and DPP

Conclusion

Natural disasters causes negative impact on human health where resilient infrastructure could alleviate the damages. DES such as solar PV can help communities more resilient such that it supplies uninterrupted energy to people in need especially those who rely on electric-operated medical devices. Hurricane Maria left more than 1,000 deaths only for 2 months and about 31.29% of the deaths are due to respiratory diseases and diabetes which seem sensitive to electricity. Two scenarios were simulated by Markov models to analyze the cost-effectiveness ratio for diabetes to figure out the characteristics in normal and interrupted situation. With 10% probability of disaster occurrance in 20 years time window, it is estimated that any measures that help to avoid the interrupted situation, would save 1,723 deaths, $676.7 million and increase about 9,042 QALY. Including respiratory diseases, the impact would be approximately twice with the fact that diabetes is attributed to 42% while 58% is from respiratory diseases for the deaths assumed to be related to lack of electricity in the event of hurricane Maria. Assuming uninterrupted electricity supply might have reduced the 31.29% of deaths occurring during the event, DES such as solar PV installation was studied in terms of economic cost and benefits.

Lifecycle Costing (LCC) by Monte Carlo simulations considering probabilistic uncertainties of electricity generation and energy market price on an annual basis were analyzed. The simulation shows that NPV is between $2.36 in millions and $2.39 in millions and DPP is between 10.45 years and 10.51 years both in 90% confidence interval. By including health benefit to the NPV estimation assuming having PV system will prevent lack of electricity during the undesirable events, the simulation shows that NPV is between $2.82 in millions and $2.85 in millions and DPP is between 9.65 years and 9.69 years both in 90% confidence interval. Considering there are 65 hospitals in Puerto Rico like the hospital in this case study, the upfront cost to install the similar type of PV system would be about $134 million. The burden of upfront cost may be alleviated through tax credits, subsidies or government incentives.

Having solar PV system in hospitals will benefit economic value and furthermore, enhance the health condition by preventing lack of electricity to those in need from disasters. It is estimated that it could save 1,723 deaths and increase 9,042 QALY while saving $676.7 million considering only diabetes assuming diabetes are sensitive to energy supply and the whole hospitals in Puerto Rico have the DES installed. While this may cost a lot like $134 million, it will be paid off within 11 years in addition to potentials in health benefit. There would be also significant economic values especially in Puerto Rico where electricity price is the highest among states and saving electricity entails higher benefits.

Appendix

Table 9: Cash flow of the PV system (1 simulation)

Year	Elec.gen(kWh)	Elec.price($/kWh)	FV($)	PV($)	NPV($)
1	756803.2	0.2433727	180144.2	169947.4	-1891717.6
2	809313.8	0.2613756	207251.5	184453.1	-1707264.5
3	763626.8	0.2851824	213232.5	179034.1	-1528230.4
4	739056.3	0.3116119	225485.9	178605.9	-1349624.5
5	782372.9	0.3343318	256470.5	191649.7	-1157974.8
6	738509.0	0.3645356	263805.1	185972.2	-972002.7
7	772877.1	0.4006138	303893.0	202106.2	-769896.5
8	772379.9	0.4301195	326139.5	204623.9	-565272.5
9	793517.1	0.4694382	366066.5	216674.2	-348598.3
10	780543.8	0.5160311	395957.7	221100.7	-127497.6
11	792880.6	0.5647753	440562.6	232082.9	104585.3
12	805464.9	0.6121416	485387.6	241222.8	345808.1
13	742284.3	0.6613015	482742.5	226328.5	572136.6
14	742315.9	0.7100172	518437.9	229305.6	801442.1
15	805948.0	0.7709265	612190.4	255445.7	1056887.8
16	758613.5	0.8395044	627174.9	246885.1	1303772.9
17	735365.9	0.9122063	660539.9	245301.0	1549073.9
18	765455.4	0.9987887	753646.8	264035.5	1813109.3
19	803276.2	1.0795254	855622.7	282794.4	2095903.8
20	792141.5	1.1612420	907641.6	283006.9	2378910.7

Table 10: PV system cash flow including health benefit (1 simulation)

Year	Elec.gen(kWh)	Elec.price($/kWh)	Health benefit($)	PV($)	NPV($)
1	803475.7	0.2414901	2247.321	184587.0	-1877077.98
2	779832.7	0.2587543	4188.107	185747.4	-1691330.59
3	741389.2	0.2773533	5853.719	182773.4	-1508557.24
4	753674.3	0.3026571	7272.666	194184.0	-1314373.22
5	802593.9	0.3277895	8470.847	212946.5	-1101426.69
6	776048.6	0.3605344	9471.776	215982.1	-885444.63
7	805866.4	0.3956981	10296.786	232777.2	-652667.45
8	775343.9	0.4293768	10965.217	231170.2	-421497.28
9	790816.2	0.4597570	11494.592	238760.2	-182737.07
10	745190.9	0.5042753	11900.767	234357.3	51620.21
11	808019.8	0.5526350	12198.087	260462.5	312082.71
12	798387.3	0.6012506	12399.510	264271.0	576353.75
13	799720.8	0.6451298	12516.733	267874.7	844228.40
14	758344.2	0.7081728	12560.305	263626.0	1107854.40
15	756942.3	0.7678073	12539.728	268552.8	1376407.19
16	778296.1	0.8413661	12463.547	283635.0	1660042.21
17	752997.1	0.9126612	12339.443	280780.6	1940822.83
18	785728.8	0.9902674	12174.308	297770.2	2238593.06
19	774377.2	1.0846082	11974.314	302294.6	2540887.61
20	811776.5	1.1837348	11744.985	323773.9	2864661.53

Table 11: Scenario in normal with QALY and cost

i	nodiabetes	diabetes	death	sum	d.qaly	d.cost
0	1000.0000	0.000000	0.00000	1000	1000.0000	4800000
1	989.4900	2.320000	8.19000	1000	935.2321	4504566
2	979.0905	4.585062	16.32448	1000	874.6516	4227137
3	968.8002	6.796167	24.40361	1000	817.9883	3966630
4	958.6181	8.954278	32.42759	1000	764.9894	3722023
5	948.5431	11.060344	40.39660	1000	715.4185	3492359
6	938.5739	13.115299	48.31084	1000	669.0542	3276735
7	928.7095	15.120062	56.17048	1000	625.6894	3074302
8	918.9487	17.075537	63.97575	1000	585.1305	2884263
9	909.2906	18.982613	71.72682	1000	547.1963	2705867
10	899.7339	20.842166	79.42391	1000	511.7172	2538408
11	890.2777	22.655058	87.06722	1000	478.5347	2381224
12	880.9209	24.422135	94.65697	1000	447.5003	2233689
13	871.6624	26.144232	102.19335	1000	418.4753	2095219
14	862.5012	27.822169	109.67658	1000	391.3298	1965262
15	853.4364	29.456754	117.10688	1000	365.9422	1843299
16	844.4667	31.048781	124.48447	1000	342.1990	1728844
17	835.5914	32.599031	131.80957	1000	319.9938	1621440
18	826.8093	34.108274	139.08239	1000	299.2272	1520655
19	818.1196	35.577266	146.30317	1000	279.8062	1426086
20	809.5211	37.006751	153.47212	1000	261.6436	1337354

Table 12: Interruption scenario with QALY and cost

i	nodiabetes	diabetes	death	sum	d.qaly	d.cost
0	1000.0000	0.000000	0.00000	1000	1000.0000	4800000
1	989.4594	2.320000	8.22055	1000	935.2033	4506813
2	979.0300	4.584915	16.38508	1000	874.5977	4231325
3	968.7105	6.795730	24.49378	1000	817.9127	3972483
4	958.4997	8.953414	32.54684	1000	764.8951	3729296
5	948.3966	11.058922	40.54445	1000	715.3082	3500830
6	938.4000	13.113191	48.48680	1000	668.9304	3286207
7	928.5088	15.117145	56.37410	1000	625.5544	3084599
8	918.7218	17.071694	64.20654	1000	584.9862	2895228
9	909.0379	18.977731	71.98434	1000	547.0445	2717361
10	899.4562	20.836136	79.70769	1000	511.5595	2550309
11	889.9754	22.647775	87.37681	1000	478.3724	2393422
12	880.5946	24.413499	94.99192	1000	447.3347	2246089
13	871.3126	26.134147	102.55322	1000	418.3075	2107736
14	862.1285	27.810544	110.06094	1000	391.1608	1977822
15	853.0412	29.443499	117.51530	1000	365.7729	1855839
16	844.0497	31.033812	124.91651	1000	342.0301	1741308
17	835.1529	32.582268	132.26480	1000	319.8260	1633779
18	826.3500	34.089639	139.56040	1000	299.0611	1532829
19	817.6398	35.556686	146.80353	1000	279.6421	1438061
20	809.0214	36.984155	153.99444	1000	261.4822	1349099

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