Improving Power Resilience and Reliability for Industry: A Novel Decision Framework to Assess Microgrid Resilience Benefits Under Different Physical Climate Risk Scenarios

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ABSTRACT

Industry is facing greater risk to their operations due to extreme weather events induced by climate change. A significant risk is loss of power because of extreme heat, flooding, and drought that impacts the overall reliability and resilience of power systems. Microgrids with a CHP base, supporting solar + storage can help improve reliability and resilience and reduce overall emissions at industrial sites. Options to utilize microgrids to mitigate extreme weather are regularly considered but, many times, are not deemed as cost-effective due to lower grid energy prices. A key limitation in deploying these systems is not considering the likelihood of grid disturbances and the resilience benefit of microgrids in the economic balance. For that to become a common practice, the full cost of business disruption due to extreme weather events needs to be better understood. This evaluation can be done by assessing the likelihood and intensity of extreme weather events. Utilizing downscaled global climate model outputs, companies can better forecast extreme weather events, particularly extreme heat and precipitation. We propose a methodology and decision framework to help companies better assess the likelihood and duration of power outages due to extreme weather and incorporate this information into their financial modeling. This framework will help them more accurately assess the value of deploying a microgrid at their facility. The anticipated result is a more resilient site with a lower emissions profile, allowing the industrial entity to reduce business disruptions, as well as meet corporate environmental emission reduction goals.

Introduction

Extreme weather due to climate change is happening now. We see an increasing trend in extreme weather events across the United States that cause catastrophic economic consequences. According to the National Oceanic Atmospheric Administration (NOAA), there were 22 extreme weather events where each had a price tag greater than $1 billion. Eleven of those events were in Texas and Louisiana, costing approximately $180 billion in damage (NCEI 2021). This is problematic as a significant portion of the United States' petrochemical industry is in a region highly susceptible to extreme events including hurricanes, flooding, sea level rise, as well as drought. Climate models indicate that states along the Gulf of Mexico, and particularly the Texas Gulf Coast, will experience a growing likelihood of more extreme weather events, like what was seen during Hurricane Harvey, as well as the major tropical storm events that resulted in widespread flooding.

Tied to the growth in extreme weather events are the number of power disturbances/outages. Over the last several years power outages have continued to increase in both frequency and duration. With greater extreme weather risk, the power infrastructure faces significant danger. We propose a methodology and decision framework to help companies better assess the likelihood and duration of power outages due to extreme weather. This framework brings together microgrid financial modeling with downscaled climate data that provide improved spatial and temporal granularity. Climate data and analytics are derived from multiple Global Climate Models (GCM) that form the backbone of the most authoritative GCM inter-comparison project (IPCC Assessment Report). The climate models allow for a better understanding of likelihood, duration, and intensity of extreme weather events which can be quantified and incorporated into the microgrid model. The decision framework allows industrial microgrid designers to understand the steps and process needed to better account for climate risks in their decision making. This information can be incorporated into their investment and operational decision making.

Increasing Power Disturbances Due to Weather Risk

According to the Department of Energy's Electric Emergency Incident and Disturbance Report (OE-417), over half of all outages in the U.S. between 2000 and 2018 were due to natural disasters (CESER 2018). The data indicates an increase in nation-wide power disturbances, with a shift from less than 50 outages on average in 2000 to over 380 outages in 2020, as shown in Figure 1. During multiple 2019 power outages, commercial and industrial customers experienced approximately $263 billion in outage costs. During that year alone, over 10 million electric power customers lost power due to major storm events, resulting in close to $140 million in lost revenue for electric power utilities. In 2017, Hurricane Harvey created a $500 million restoration price tag (Britt 2017).

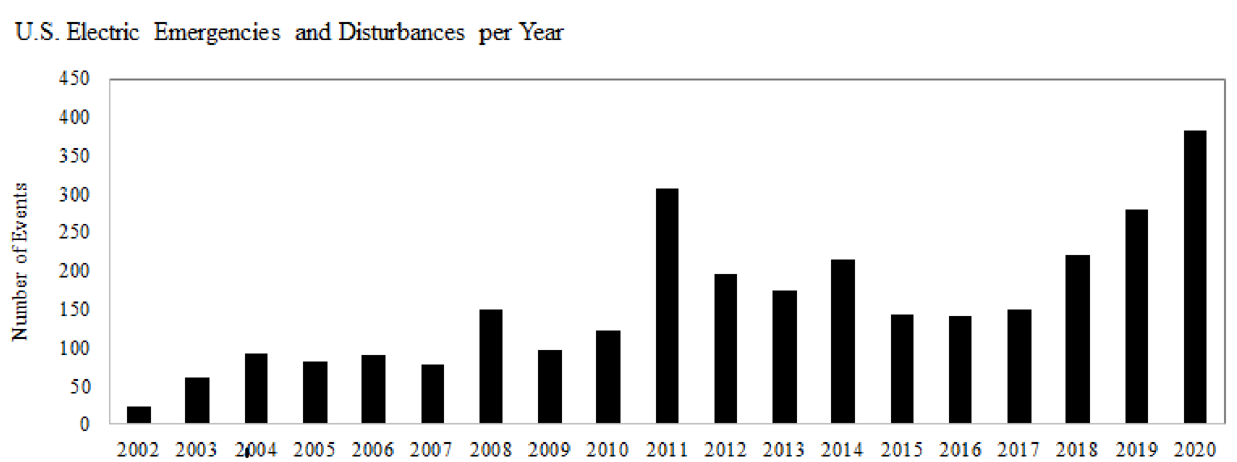

Figure 1: The U.S. DOE's Electric Emergency Incident and Disturbance Report shows an increasing trend in power disturbances between 2002 and 2020. Image made with data from (CESER 2018).

With the anticipated increase in extreme weather events, due to climate change, organizations will have greater incentive/motivation to identify strategies/investments that will improve resilience and ensure operational continuity. Microgrids[1] with combined heat and power (CHP) can be a key technology that mitigates outage risk. However, the deployment of microgrids is stymied due to upfront costs and the inability to value the lifecycle resilience

[1] A microgrid is a self-sufficient energy system that serves a discrete geographic footprint, such as a college campus. Within microgrids are one or more kinds of distributed energy (solar panels, wind turbines, combined heat & power, generators) that produce its power.

benefit of these systems. Most investment models do not consider the likelihood and intensity of extreme weather and their impact on business continuity. With the growing evidence of extreme weather induced power outages, it is important that decision frameworks are available that consider this risk by quantifying the value of resilient microgrid systems.

Microgrids and the Value of Resilience

According to the company Emergen Research, “the global microgrid market size was valued at $28.80 billion in 2019 and is forecasted to reach $61.18 billion by 2027, at a [compound annual growth rate] of 10.5%.” This company's report also states that “the market is mainly driven by increasing demand for uninterrupted and reliable power supply all across the world”, the increase in policies and initiatives promoting energy efficiency and the trend toward renewable and distributed energy generation will also drive demand for microgrids (Emergen Research 2020).

Industrial companies are under the influence of these drivers too and they are, in fact, good candidates for hosting microgrids due to their energy intensity and their need for reliability. The initial investment required for a microgrid is highly related with its goals. For example, it is generally accepted that it is necessary to invest in renewable energy and efficient technologies to minimize the environmental impact of a microgrid. At the same time, a resilient microgrid will require a certain level of redundancy in the energy generation systems (i.e., N+1) or additional energy storage systems like battery or thermal storage. These additional features come at a cost for the end user that is not always easily recoverable with the energy savings generated, typically resulting in paybacks around ten years or more. However, the industrial sector is very competitive, and many companies do not use to implement projects with paybacks over five years, a very challenging framework for resilient microgrids.

Incorporating the value of resilience in the cost-benefit analysis can support the feasibility of a microgrid project, but the value provided by a resilient microgrid is different for each industrial company, and not always easy to quantify. The Value of resilience can be estimated based on the cost of outage or Value of Lost Load (VoLL) (Schröder and Kuckshinrichs 2015). Many VoLL techniques have been studied in the literature using direct or survey methods from end users and indirect methods from statistical methods (Schröder and Kuckshinrichs 2015; Ajodhia, van Gemert, and Hakvoort 2002; Caves, Herriges, and Windle 1990; de Nooij, Koopmanns, and Bijvoet 2007; Lijesen and Vollaard 2004; London Economics 2013; Sullivan and Keane 1995; Woo and Pupp 1992). These methods include power disturbance studies, willingness to pay/avoid, direct costs of damage caused by outages, the production function, and revealed preference (Schröder and Kuckshinrichs 2015). Sullivan et al. (2015) and Schellenberg & Larsen (2018) provide a meta-analysis of utility customer surveys conducted between 1989 and 2012 using similar interruption cost estimation or willingness-to-pay/willingness-to-accept methods. The estimated general customer damage functions for different seasons, times, U.S. regions, and customer types resulted in the development of the Interruption Cost Estimate (ICE) Calculator (Sullivan, Schellenberg, and Blundell 2015; Schellenberg and Larsen 2018; LBNL 2018). Laws et al. (2018) uses VoLL parameters established in Sullivan et al. (2015) to estimate cost of resilience where maximum cost to island[2] is the Net Present Cost (NPC) of a scenario with resilience valued minus the NPC of the same scenario without resilience valued (Laws et al. 2018). Greater outage costs mean shorter paybacks for resilient microgrids for the same

[2] The ability to operate independent of the power utility grid.

probability of occurring than lower outage costs. These metrics evaluate customers' damage in an outage or desire to avoid a future outage. However, they do not integrate the role of climate change in increasing frequency of outages. Further, since the outage costs differ for each end user, and although these are good methods to provide estimations of that value across industries and outage types (Laws et al. 2018), each user should identify its own value loss to guarantee the accuracy of the economic viability of the microgrid.

Decision Framework Implementation

In this paper, we propose a framework for industrial companies to better design tailored microgrids that meet their cost-efficiency and resilience goals. This work incorporates the value of lost load, the risk of power outages due to climate change, and the cost of resilience to power outages through a microgrid. Downscaled climate data is incorporated into the decision-making processes to help companies estimate oscillations in their future energy demand, also plugging into the company's emergency plans to estimate the cost of potential power outages. These costs are ultimately incorporated into the cost-benefit balance of a resilient microgrid to better assess its value. *Figure 2* shows the steps of the decision framework. The goal for this process is for an industrial company to be able to develop a plan to understand their outage risks and support the design process of a resilient microgrid to mitigate those risks.

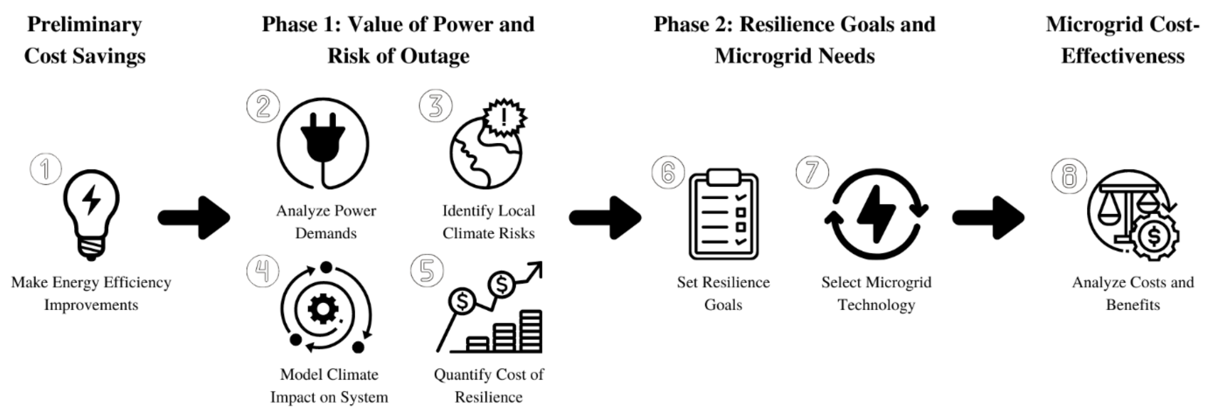

Figure 2: Steps of the decision framework.

Step 1: Make energy efficiency improvements

According to EIA in 2019, the industrial sector accounted for 35% of total U.S. end-use energy consumption and 32% of total U.S. energy consumption (EIA 2020). Industrial must conduct an energy efficiency audit or even implement an ISO 50001-based energy management system, prior to addressing the design of a microgrid. Each will provide valuable information for the microgrid planning process. Additionally, energy efficiency measures are generally cost-effective, saving energy and operating costs after implementation. Microgrids must be designed for resilience, but they also provide services to the facility throughout the rest of the year. Microgrids for less efficient facilities will require higher investments than for efficient facilities, both from the installation and the operations point of view. Streamlining electricity demand before determining power demands in step 2 allows the industrial user to plan for a smaller system and a lower associated expense, and it reduces the load a microgrid needs to manage during a contingency.

\Phase 1: Value of Power and Risk of Outage

The next phase of the decision framework is to value power demand and the risk of outage. In this phase, the industrial user should conduct a power demand analysis, identify local climate risks that might disrupt power, model the climate impact on the electric power system on which they rely, and then quantify the cost of resilience.

Step 2: Analyze Power Demands

To conduct a power demand analysis, the industrial user should identify the peak and minimum power loads, as well as the production, stand-by, and maintenance loads.

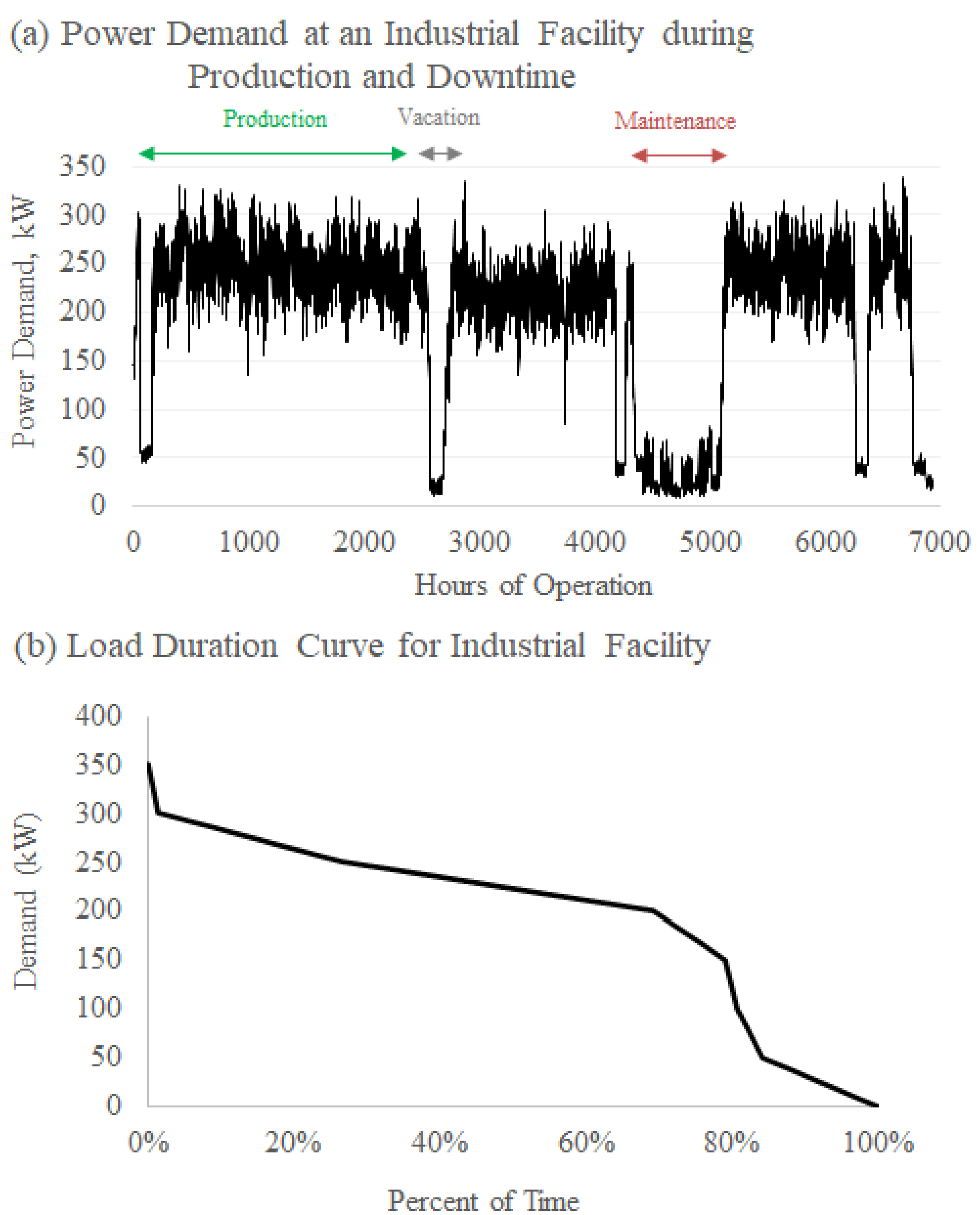

Figure 3. (a) Extract of power demand curve of an agar-agar extraction plant and (b) Load duration curve at an agar-agar extraction plant.

The additional initial investment a resilient microgrid requires is hard to justify without operating it in a cost-effective manner throughout the year. Thus, a microgrid must be designed for its highest efficiency during the most frequent power demand scenarios. Figure 3a shows an example load curve for an agar-agar extraction plant, and figure 3b shows the hours in a year for which the plant's load is over a certain power capacity. Load during production hours oscillates between 150 and 350 kilowatts (kW). However, while the plant's load reaches 200 kW for 69% of the year, it only reaches 250 kW for 26% of the year and 300 kW for 2% of the year, or 200 hours total. Under those operating conditions, the highest efficiency of the microgrid should be guaranteed in the range going from 50 to 200 kW. Standby loads are under 50 kW for this process and maintenance loads oscillate between 20 and 80 kW. Identifying the consumption of as many energy sub-systems of the industrial process as possible during the energy audit will help quantify the critical load of the whole industrial process in further stages of this process.

Step 3: Identify Local Weather and Climate Risks

There are a range of impacts associated with climate change, but understanding the locational risks is important to narrow down which climate indicators are most important to assess for a specific industrial user. Local climate risks, such as frequency, duration, and intensity of extreme weather events like droughts, extreme precipitation, and heatwaves and the historic length of the power outage associated with previous events should be identified.

Power distribution companies, including local utilities, publish interruption data, including the System Average Interruption Frequency Index (SAIFI) which is the average number of interruptions that a customer would experience, and the System Average Interruption Duration Index (SAIDI), which is the average outage duration for each customer served. Quality indicators of the local power grid like SAIFI and SAIDI provide good insights on the historic frequency and disruptive potential of weather-related power blackouts on the manufacturing process. Additionally, for new construction, proximate facilities can provide valuable insights on how frequent power blackouts are in the area. All available information should be used to estimate the length and frequency of power outages. While the power grid quality indices provide historic data and trends, downscaled climate models provide valuable insights into frequencies and lengths of different types of natural disasters that might oscillate in the future, leading to different frequencies and lengths of power blackouts. In this process it is assumed that similar natural disasters would lead to similar length of outages determined via the SAIDI and SAIFI indices. For example, a second flood will produce a similar power blackout as the first for the same flood levels.

One of novelties of this procedure is the incorporation of downscaled GCM to assess the future likelihood of certain disasters to occur in the future. GCMs are used widely in the climate science and climate change adaptation community as an approach to characterize and quantify future climate change. GCMs provide a set of future climate scenarios, including RCP4.5 (greenhouse gas reductions) and RCP8.5. The climate data is downscaled to 1/16th degree (~7km) spatial resolution and daily temporal resolution. For each climate scenario, daily precipitation- and temperature-related variables have been downscaled at 1/16-degree spatial resolution from the current year up to the year 2100. This granularity allows to the user to assess climate risk at a specific asset location or a portfolio of assets. Figure Y shows an example of the capability of GCM using variation in cooling degree days over time in a nine-county area in the Houston-Galveston region of Texas. An increase in cooling degree days means the power demand for cooling will increase, impacting individual users as well as the power grid on which they rely.

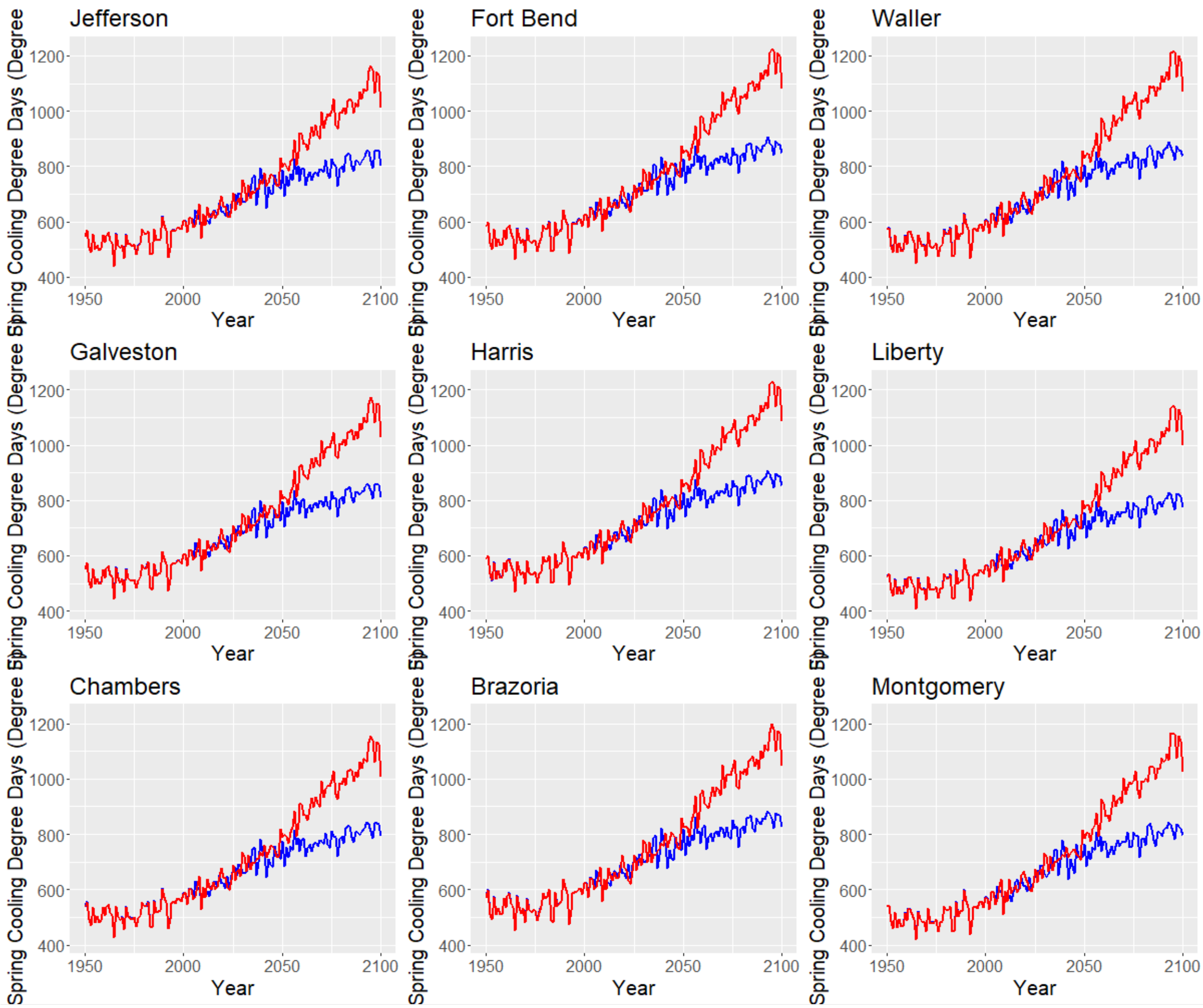

Figure 4. Example GCM output for nine county area within the Houston-Galveston region of Texas.

Step 4: Model Climate Impact on System

While there are likely multiple risks that could be identified in a local area in step 3, it is important to focus the modeling efforts on how the climate impacts would affect the most critical aspects of the industrial process in two ways: changes in the power demand curve that might require different microgrid configurations than the historic power demand, and the frequency and length of potential power blackouts.

Frequency, duration, and intensity of extreme weather events (e.g., droughts, extreme precipitation, and heatwaves, etc.) can be derived from GCMs with a certain level of confidence. These climate indicators can impact the performance of industrial processes in both short- and long-term power generation capabilities and power demand. For example, extreme precipitation could lead to flooding that might damage different assets at the plant like the onsite power generating equipment or substations. An increase in the number of days for which temperature falls below 65ºF (heating degree days) leads to an increase in energy demand for space or process heating; a similar increase in the number of days on which temperature reaches above 65ºF (cooling degree days) leads to an increase in energy demand for space or process cooling.

Factors like temperature and humidity also have an impact on the energy performance of other industrial services such as compressed air or vacuum, and on industrial thermal processes, generally. Some rules of thumb can be applied to estimate the increase in energy demand; for example, "a 5°C increase in air inlet temperature will lead to a 2% reduction in your air compressor's performance."[3] However, estimating the influence of ambient temperature increases on the cooling demand of some industries, such as a slaughterhouse or a fish processing plants, would require advanced energy modeling tools or historic data analysis techniques. In the end, the type of industry and the initial energy audit will define which energy usages require additional modeling to be integrated with the downscaled climate models.

Step 5: Quantify Cost of the Lack of Resilience

To determine the value of resilience, information should be collected regarding the factors that influence resilience, the value of lost load, and the cost of resilience. As mentioned above, each industrial process, and even each company within the sector, might have different resilience needs. Some of the most common factors that influence the resilience needs are:

- *The type of severe weather.* Different severe weather events might affect the industrial processes in the short term such as hurricanes, tornadoes, or floods, or even in the mid-term like droughts or high temperatures. The former will require emergency planning while the latter will require mid-term planning to continue operating in the most cost-effective and safest manner possible.

- *The nature of the services or products provided.* As an example, a kitchen furniture factory might decide to close the facilities when there is a flood risk to keep their employees and facilities safe while critical facilities like water treatment plants apply shelter-in-place protocols to continue operating.

- *The nature of the industrial process.* Some industrial processes like those employed at frozen food factories can resist brief power outages with minimal losses due to the thermal inertia of their facilities (they are typically well insulated). However, steel foundries or wastewater treatment plants, on the other hand, see their production chains impacted at the onset of a power outage.

Once the factors that influence resilience have been identified, the Value of Lost Load (VoLL) can be determined. As mentioned before, there are multiple methods in the technical literature for determining the VoLL and associated cost of resilience. The site-specific VoLL can be determined using a site survey identifying the specific costs associated with the various power consumption scenarios in step 2 and determining willingness-to-pay to avoid an outage of various lengths associated with the SAIDI and SAIFI indices. Additionally, emergency and contingency plans must be considered in quantifying the site-specific VoLL. The average costs incurred per hour due to each of the local climate risks scenarios and the emergency or

[3] https://www.atlascopco.com/en-uk/compressors/compressed-air-tips/efficient-compressed-air-management

contingency procedures adopted (standby, stop or keep on the production chain working as usual) are calculated based on the duration estimated via the downscaled climate model.

Table 1: Example of Estimated Costs per Climate Risk for a Certain Company

Risk	Duration	Protocol	Concept	Amount
Flooding leading to power blackout	Up to days	Shelter in place and continue operating	Additional work hours	$4,000 per hour
Heat Wave	Up to weeks	Business as usual	Additional energy costs	$100 per hour
Cold wave leading to a sudden power blackout	Up to days	Sudden process shutdown that requires repairs and calibration.	Production, salaries, stock losses, re-starting costs, and re-calibration	$10,000 per hour
Cold wave leading to a sudden power blackout managed by the microgrid	Up to days	Process in standby.	Production, salaries, stock losses.	$5,000 per hour

A general value of lost load can be estimated using the Interruption Cost Estimate Calculator (https://www.icecalculator.com/home) developed by Lawrence Berkeley National Laboratory and Nexant, Inc. The VoLL must be incorporated with likelihood of power, fuel, or water outage associated with climate risks determined in step 4. Because the information provided is a general estimation, it may lead to less accurate results than a site-specific analysis.

The cost of resiliency should be compared to the cost of the resilient microgrid scenario, as determined in phase 3. The cost can be incorporated in dollars by event or based on kWh of energy not served. The indicator can be adjusted to fit the information available. A simplified calculation of the cost of resilience is included in Equation 1 where the total cash flow of non-resilience is the sum of the product of VoLL and duration of outage, Δt, associated with each power outage risk pathway, i, identified in step 4.

Equation 1 $$C_{non-resilience} = \sum(VoLL_i \times \Delta t_i)$$

Phase 3: Resilience Goals and Microgrid Needs

Manufacturing processes usually have characteristic energy demand profiles, based on the type and the sections of the manufacturing process they run at the same time. The information provided by the load duration curve in step 2 can help define the size of the microgrid from both a cost-effectiveness and resilience standpoint. Resilience solutions increase their profitability dramatically when they can contribute to an improvement in the cost-efficiency of the process daily. Site-specific needs should be considered as some technologies are more dispatchable than others, and some industrial processes, such as food processing plants, might have inertias that ease the short-term resilience needs. In this next phase of the decision framework, the industrial users should set their resilience goals and select the appropriate microgrid technologies for their needs.

Step 6: Set Resilience Goals

It is important for industrial processes to define the load levels that apply to their emergency or contingency plans. Given their resilience needs and the type of disruption, industrial processes might adopt different strategies for adapting to power disruptions or blackouts, such as:

- Use of onsite generation to back up the entire process to continue operating in the short or long term and
- Use of contingency power to aid in the transition to stand-by or secure mode, followed by halting the process until the conditions are met to restore operations.

Based on resilience needs and the energy consumption data per sub-system obtained from the energy audit, a profile of the power demand during different contingency situations can be developed and the resilience goals of the microgrid defined. Typically, the resilience goals are stated in terms of the energy needs in kilowatts (kW) to be backed up during a certain duration in hours. Microgrids can implement strategies without interrupting the power supply, but the costs associated with real-time transitions are higher than the costs for microgrids that must disconnect from the grid to start or restart their local generation assets. Additional efficiency or environmental goals should also be identified and incorporated into the microgrid selection, as well.

Step 7: Select Microgrid Technologies

Once the industrial user identifies their resilience goals and the capacity needed for their system, the design team need to choose the candidate technologies for the microgrid solution. The microgrid should be able to withstand the most impactful climate risks identified in step 4 and *Figure 3*. For example, CHP is good for processes that demand both thermal energy and power at the same time but not if the thermal demand in the process is low. If the user only requires power and wants to have net zero emissions, they will need to rely on solar power and battery storage. Different technologies have different abilities to withstand natural disasters or storm events. The table below shows a comparison of the how different natural disasters affect the performance of different technologies, being one of the most resilient combined heat and power.

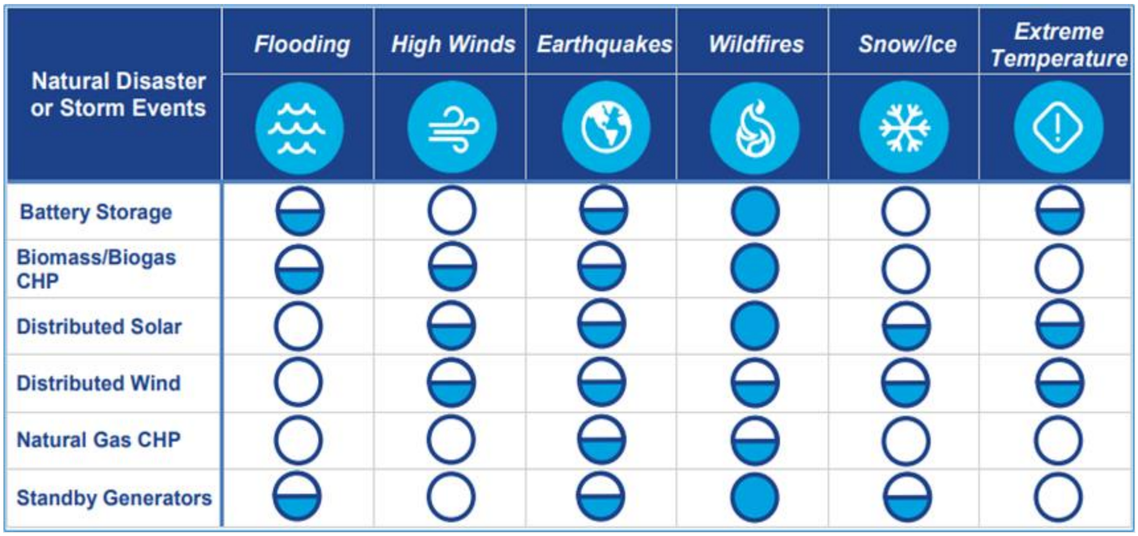

Figure 5: Microgrids can also be affected by climate risks; choosing a microgrid that will be more resilient to local climate risks is important. Image made with data from (Better Buildings 2018). Source: US Department of Energy Resiliency Accelerator

Once the candidate technologies have been selected, the usage of computational optimization techniques (Gamarra and Guerrero 2015) or existing software tools are highly recommended to explore as many combinations of energy technologies and sizes as possible in a short period of time. The existing computational optimization techniques for microgrid feasibility analysis solutions are more intuitive to use but less customizable and generally provide a lower level of detail in the result. The models are often based on optimization algorithms with the goal to find the energy generation and energy storage mix for the microgrid which satisfies the power demand at the lowest cost, usually considering environmental and reliability constraints. Conversely, software solutions can adequately find the most cost-effective option to provide the minimum and maximum power demands but are less able to capture design incompatibilities and performance issues related with intermediate power demands. Some technology aspects will need to be double-checked during the engineering stage of the microgrid establishment process, including:

- Potential combinations of the minimum and maximum power generation limits per generator when the microgrid is isolated from the main grid or there is a power blackout,
- Ramp-up capabilities and down and up times per technology when the microgrid is isolated from the main grid or there is power blackout,
- Efficiency of the installed battery and thermal energy storage, as they are great for providing resilience but might be in use if the microgrid is properly sized for the load of the industrial site, and
- Number of annual starts and stops required at the facility, as the more renewable energy participates of the microgrid, the more those starts and stops are required for the dispatchable energy generation resources, such as reciprocating engines or natural gas turbines, shortening their lifespan and increasing the maintenance frequencies and costs.

Additionally, microgrid controls have not been fully standardized yet, resulting in many solutions varying in price and quality. Hardware-in-the-Loop (HIL) testing of the whole model is recommended to make sure the functionalities desired are fully executable by the technologies selected, but not required as part of this methodology.

The costs of investment and operations and maintenance (O&M) for the selected microgrid must be determined as this cost must be compared to the cost of resilience to understand if costs outweigh benefits. Equation 2 shows a simplified version of this calculation.

Equation 2
$$C_{Microgrid} = \frac{Investment + O\&M}{discount\ factor}$$

Step 8: Analyze Costs and Benefits

The final step of the decision framework is to analyze the costs and benefits of the chosen solution. To do so, the total cash flow, C_{Total}, is calculated as the cost of non-resilience determined via steps 2-5 in Phase 2: Value of Power and Risk of Outage ($C_{non-resilience}$) less the cost the resilient microgrid determined via steps 6-7 in Phase 3: Resilience Goals and Microgrid Needs ($C_{Microgrid}$) as shown in equation 3. If the cost of the baseline case (do nothing against the climate change impact) exceeds the cost of the resilient microgrid ($C_{Total} > 0$), the microgrid solution will be profitable.

Equation 3
$$C_{Total} = C_{non-resilience} - C_{Microgrid}$$

Additional capacity might be available to the user; the optimal microgrid size will be equal to the net present value of resilience. However, industrial companies benchmark their future investments, seeking lowest paybacks and highest returns. Therefore, it is important to calculate key financial indicators such as the Net Present Value (NPV) of the Internal Rate of Return (IRR). In this process each company will define its own interest rate, and the same interest rate must be selected for all the benchmarked projects. That interest rate is usually based on the cost of capital and the profitability the company is willing to obtain with the investment. Lower interest rates will result into higher NPVs and IRRs, while higher interest rates will make more challenging for those indicators to show positive values.

Conclusion

This paper presents a methodology to incorporate climate risks into the operational planning of industrial companies, and more importantly, provides a framework for the decision making during the initial stages of the establishment of a resilient microgrid. The process starts with an energy audit or an energy management system optimizing the power demand and providing information of the energy consumption of the different sub-systems in the industrial plant. After the energy audit, the framework continues with phase 1, Value of Power and Risk of Outage. The first step in phase 1 is to analyze the power demand of the industrial process, including the different configurations and status of the operations of the plant. The knowledge acquired during these first two steps will be used in later steps of the microgrid planning processes. After analyzing power demand, local climate risks must be identified using downscaled climate risks data. Modeling the influence of climatic factors into an industrial project can be time-consuming, so priority should be placed on the climate risks with the highest potential to cause area-wide power disturbances such as hurricanes, tornados, or flooding; subsequent consideration can be given to factors impacting the energy demand of the plant. For some systems, such as air compressors, industry-recognized rules of thumb might be used to simplify the calculations of the oscillations on the energy demand of the process; other systems might require historic energy demand data for the plant and more complex data analysis or modeling techniques. The information in the climate models is used to quantify the economic impact the climate risks would have should no action be taken to mitigate them.

The next phase of the framework focuses on setting the resilience goals for the industry process, based on the existing emergency and contingency protocols, and selecting the microgrid solution. The information gathered during the energy audit is helpful at this stage to quantify the energy demand of the process during the contingency and emergency scenarios, and to pre-select the technologies and sizes of the future microgrid components. At this stage, microgrid optimization techniques or commercial software can be used to identify the right configuration of the microgrid, but they must be double-checked for incompatibilities and re-defined, as needed.

The investment cost of the microgrid, the operation, and maintenance costs should then be determined. Once the microgrid is selected, the final step is to compare the cost of non-resilience identified in phase 1 to the cost of the microgrid solution identified in phase 2. The user should also evaluate the cash flow of the microgrid project using an interest rate consistent with the one used in other projects that might be competing with the resilient microgrid. Should the costs of non-resilience exceed the cost of the resilient microgrid, the solution is cost-effective. Additional economic indicators such as the Internal Rate of Return or the Discounted Payback Period will provide more specific information used to benchmark this investment with other the company might be considering.

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