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### **A Comprehensive Metrics-based Climate/Resilience Plan and Investment Strategy**

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#### **SUMMARY**

Climate change has been acknowledged as an area of concern worldwide, being increasingly experienced through the impacts of record temperatures, severe storms, flooding and other extreme weather events. Numerous countries around the world have created or adopted plans and formed agreements and coalitions to mitigate climate change with tiered goals.

Motivated by this shift in the policy landscape, it is recognized that climate change considerations will evolve as part of the process for a variety of business areas and entities. In an environment with aggressive climate goals and mandates, on the one hand, and increasing monetary opportunities through new investments for climate change improvements on the other, we envision that climate change plans need a drastic and immediate make-over in two axes : (i) from standalone decisions to integrated decisions and (ii) from qualitative, directional analysis to quantitative modeling. This paper proposes ways to structure comprehensive and effective climate strategies, applicable to cities, utilities, states and even countries. The proposition is that of comprehensive climate/resilience strategy, embracing solutions rooted in the built infrastructure, services and social environment. The solutions can be mitigation or adaptation solutions.

The paper puts forth the steps of such a climate/resilience plan and details on the current gaps/roadblocks to implementation. The first missing piece of the puzzle is that of the short spectrum of commonly used and accepted metrics, particularly for resilience and the social environment status. This paper makes propositions on important properties that metrics considered should possess. Metrics should be case-specific and promote continuous improvement and benchmarking. Metrics should also not be inter-dependent, which would in essence implicitly prioritize the same targeted final outcome. The converse is also an important consideration to include: if multiple solutions impact the same metric, proper separation and quantification of each measure's stand-alone contribution is critical to obtain.

Next, the paper focuses on vulnerability assessment: assets and areas should be prioritized based on overlaying engineering criteria (like low capacity headroom) with social indices. This amounts to a highly granular locational evaluation to develop a heat map of pain points.

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Then, the paper presents the mathematical foundation for a granular, quantitative investment prioritization akin to a knapsack problem, where the selection is amongst a portfolio of climate change measures. Each measure has a dollar cost associated with deploying and a conditional expectation that is measured in the improvement of climate change metrics, of network resilience and of the social environment status. The goal is to select the solutions that collectively offer minimization of the total costs.

Last, the paper attempts to associate measures to metrics and to classify the relationships of certain types of measures to metrics. For example, climate change adaptation measures are not expected to have an impact on the climate change metrics. Conversely, health and social environment metrics are a universal receiver as they are affected by climate change measures in the mitigation and adaptation categories stemming from either the built or social environment. All in all, the climate change mitigation measures typically have close to linear relationships with climate change metrics. On the other hand, adaptation measures, and primarily adaptation measures rooted in the social environment, need an intermediate metric to be translated to the final metric that is a dependent variable of the optimization and those relationships are expected to be heavily non-linear.

## **KEYWORDS**

Climate change, mitigation, adaptation, resilience, investment prioritization, network sensitivities.

Climate change has been acknowledged as an area of concern worldwide, with impacts including record-breaking temperatures and severe storms. In just the first seven months of the year (2021) multiple manifestations of climate change broke international news; the recent deadly floods in China in July, the cold front in Texas in February as well as the heat wave in the Pacific Northwest in June are just a few examples. Climate experts are also increasingly able to attribute the intensity of such events to climate change [1], [2]. These examples show that climate change is here, it is spreading across the globe and its direction cannot be assumed, as we saw with the normally very warm state of Texas get hit with extreme low temperatures.

## **Built versus social environment**

The consequences of climate related extreme events can be thought of along two main axes: (i) the built environment and associated services, including residential and commercial buildings, city infrastructure, electrical grid assets, utility services and (ii) the health and social environment, that refers to the impact to the communities in terms of health, social order, accessibility and fairness. The former is predominantly focused on how the hazard interacts with the physical systems, while the latter takes into consideration how the overlay of these physical systems intersect with pre-existing vulnerabilities to amplify the impacts of a disaster. Physical systems are often the focus on engineering solutions. Examples can include increasing wind ratings, flood resistance, and other measures to harden this infrastructure from incoming threats. The social environment can be understood through a number of lenses that predict vulnerability. These include health status, socioeconomic status, access to transportation. But while these environments are often talked about as separate constructs, they influence one another, and investments in the built environment have the potential to enhance as well as diminish social constructs, directly and measurably affecting disaster vulnerability. And while the built environment has traditionally had more readily available performance metrics, there is a growing body of literature attempting to quantify social vulnerability. The electric grid is a critical part of this relationship, that is increasingly being recognized as a community lifeline [3] among emergency managers that facilitates the functioning of civil society.

## **The relationship of climate change to resilience**

The impacts of climate change to the electrical grid and its services are commonly discussed under the related topic of resiliency, where the manifestations of climate change are called “high-impact low-frequency” events. This paper is focused on climate change strategies and starts by recognizing the electrical grid as a key enabler for many services. Climate change solutions are categorized to mitigation and adaptation. The former refers to solutions that are trying to slow down the pace of climate change. Such solutions include energy efficiency, renewable penetration and transportation decarbonization amongst others. Climate change adaptation solutions, on the other hand, refer to actions done to protect the built, social and health environments from the (mitigated but nonetheless existent) climate change manifestations. As a result, electric grid-focused solutions under the resilience umbrella, aka grid reinforcements against said high impact low frequency high impact events are categorized as a subset of climate change adaptation measures.

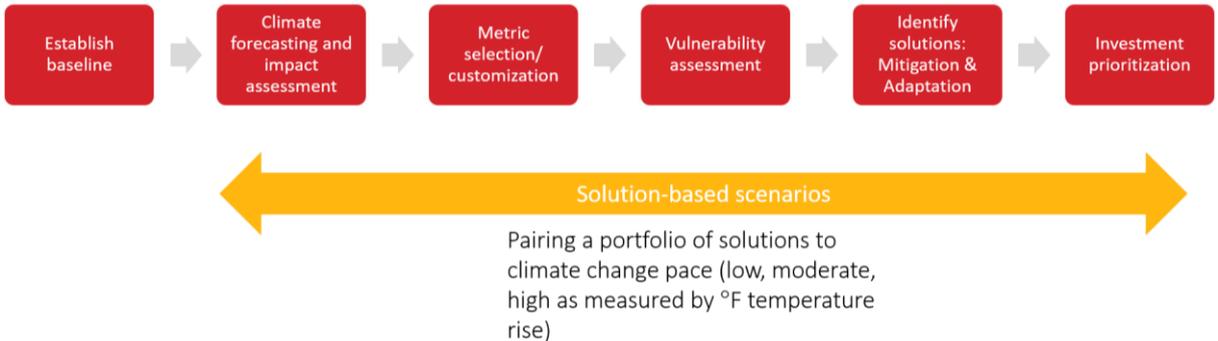
## **Mandates & opportunities**

The regulatory push for climate change mitigation and adaptation measures is increasing globally. United Nations’ Paris Agreement, adopted in 2015, is an international agreement to limit global warming to below 2 degrees Celsius [4]. Each participating country is to submit a climate action plan to reduce greenhouse gas emissions, as well as adaptation measures.

In United States, federal level goals range from emission reductions to transportation electrification. Very recently, a bipartisan infrastructure bill that includes budget for transportation electrification, carbon capture technologies, and electricity transmission investments to facilitate renewable energy has been drafted [5]. At the state level, twenty-four states have set greenhouse gas emission targets, which can be in the form of net-zero or emission reduction pledges [6]. The state of California, for instance, has set both: a net zero target by 2045, and a target to reduce emissions 40% below 1990 levels by 2030. In the electricity sector front, many states have adopted renewable, alternative, or clean portfolio standards or a combination of those. Industry level pledges are also taking place across different industries. As such, more than 100 companies have signed Amazon’s Climate Pledge. Shell, a global energy company, has pledged to become a net zero emissions business by 2050 [7].

### A comprehensive, metrics- based climate/resilience plan

This paper focuses on ways to structure climate strategies and plans applicable to a variety of entities, from cities, to utilities and states and proposes a tiered, metrics-based climate/resilience plan. This section details the steps comprising such a plan, as seen in Figure 1 below.



**Figure 1. Climate/ resilience plan workflow**

The steps comprising the climate plan are as follows:

- 1) Establish baseline: Collection of indicators of system state, regulatory mandates, planning and operational practices, operational and functional concerns. This is the status-quo. For future years, the base case scenarios are in essence a forecast of the current state of affairs continuing business-as-usual planning and operations, where climate plans do not evolve, and policies and measures stay flat and do not get progressively restrictive.
- 2) Localization of forecasting of climate change impacts. Commonly used and accepted metrics for climate change and its manifestations exist (min/max temperatures, sea level rise etc). In this paper, we propose a scenario-based formulation where we come up with three tiers of climate change scenarios, measured by temperature rise: low, moderate, high. The cutoffs/thresholds for each tier would be case-specific (see below).
- 3) Metric selection refers to the progress areas that are to be improved with the proposed solutions. In general, metrics can be classified in three buckets: climate change mitigation metrics, built environment metrics and health and social environment metrics.
- 4) Vulnerability assessment is the localization of system pain points. This includes areas with currently poor reliability, areas with critical infrastructure, areas with particularly aging equipment, downtown areas or even areas of specific system stress due to

microclimates. This step would identify said pain points and also prioritize them with comparative weights to guide investments to the relief of the most critical elements from an engineering and community perspective. The latter refers to the social index of assets and infrastructure (equity, service area, type of asset/infrastructure).

- 5) Pairing of narrowed-down metrics with mitigation and adaptation measures. These will be rooted in either the built environment (electric grid, city infrastructure) or the health and social environment.
- 6) The final step is that of investment prioritization.

The following sections focus on two key steps above: Section IV lists the properties that resilience metrics shall follow. Section V focuses on the vulnerability assessment, while Section VI details the mathematical process followed for investment prioritization.

## The search for relevant metrics: needed properties

The crux of the majority of the steps of the climate/resilience plan is nested in the need to develop metrics to monitor performance as well as to set targets. The metrics are around three axes:

- I. Climate change metrics: Metrics showing the prevalence and pace of climate change. Climate change can be quantified with multiple metrics, including targets for greenhouse gases, targets for temperature rise, ice melt area or sea level rise. Such metrics are already matured in the environmental/ climate change literature and industry studies.
- II. Grid status metrics: These metrics show the capability of the grid to withstand high impact low frequency extreme events aka how resilient is the grid. Heretofore, these metrics will be called resilience metrics. An up-to-date literature review and forward thinking was outlined in [7], that concludes that currently, there are no agreed upon resilience measures, although there is traction, especially in the utilities field, to start developing such metrics.
- III. Health and social environment metrics: These metrics show the effects of measures on the citizens and society. As an example, reduced levels CO<sub>2</sub>, would result in better health for the locals. A hardened grid with fewer interruptions would have consistent accessibility, fairness and social order.

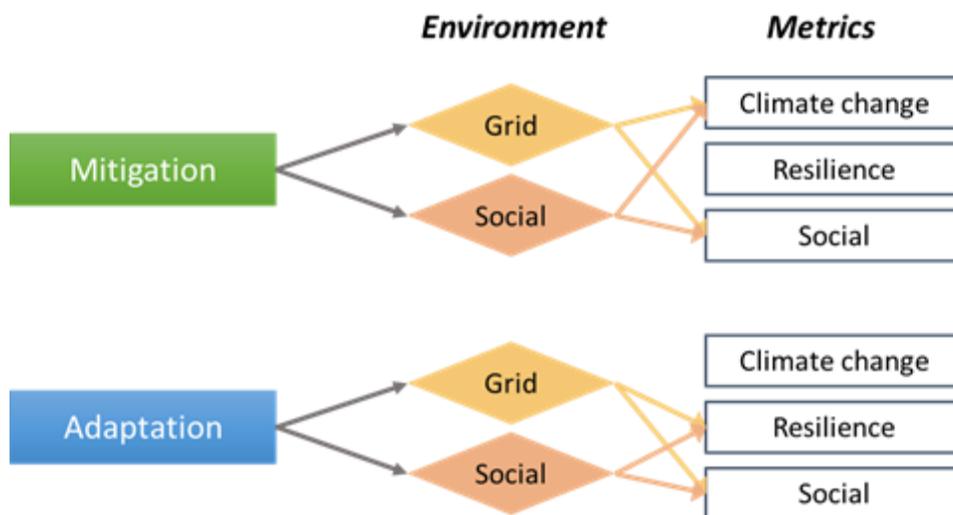
Nowadays, there is just a narrow spectrum of commonly used and accepted resilience and social environment metrics. The latter tend to rely on relative inequalities in areas like access to transportation, healthcare, economic opportunities, among other aspects over space and time. Additional relationships of concepts such as social cohesion and social capital have also become powerful predictors of disaster outcomes and the dynamics of resilience. These measures look at proxy such as census response rates, crime rates, migration rates, creative class employment, among many others. But while there are many measures, more work is needed to determine weighting within other quantitative measures [7].

This paper focuses on establish a roadmap for impactful resilience metrics, by means of listing properties they should exhibit. Resilience metrics should:

- Be cognizant of the “no one-size-fits-all” concept of resilience. In other words, universal problems, granular solutions means that a stable grid with infrequent and moderate (or low) impact weather events, with fast restoration in the face of such events when they unavoidably occur, is the target state for electric power systems across the globe. However, the unique combination of climate, geography, system state and other regional and operational differences dictate different metrics to assess state and progress and different solution portfolios [9].
- Resilience metrics should promote continuous improvement and enable benchmarking. [10] showcases that the actual impact of extreme events is nowadays routinely

underestimated due to the calculations used that get disproportionately skewed by the low frequency. Historical data is retained of reliability metrics only, meaning that data that has been related to extreme events is not included in the reliability metrics calculation and are discarded and not retained. Additionally, the indirect impacts of outages may play out over longer time-scales with residual health, economic and other social costs that are not accurately valued under current investment criteria.

- A couple more challenges, in addition to the uncharted territory of resilience metrics itself, rise in the presence of multi-faceted targets. A critical challenge in selecting metrics for the investment optimization is that metrics should be independent of one another. For example, sea level rise and area of ice melting are related to each other. This would put additional emphasis on essential the same final goal (similar logic to the clustering quantities that need to be independent.). Further, rising temperatures and increased flooding may affect marginalized communities within urban environments more than other communities due to legacies of inequitable social policies and urban planning practices.
- Further, double counting should be avoided, but at the same time, solutions that tackle more than one issues concurrently should be evaluated as more valuable. Conversely, if multiple solutions impact the same metric, proper separation and quantification of each measure’s stand-alone contribution is critical to obtain. An example of how challenging this can get is trying to estimate the change of the general population’s respiratory health as a social environment metric. If the city is promoting transportation decarbonization by building bike lines, promoting shared bicycle systems etc, then the respiratory health metric is improved concurrently by (i) the physical exercise of biking and (ii) the lesser CO2 emissions due to less residential car miles driven lead to better air quality, hence improved respiratory health. Figure 2 below visualizes the relationships.



**Figure 2. Relationship between environment and metrics, both for mitigation and adaptation**

Mitigation measures, built and social environment-based alike, impact climate change and social environment metrics but are generally not directly impacting resilience metrics. Adaptation measures are generally not expected to directly affect climate change metrics, but will impact resilience and social environment metrics. In other words, a right-to-left view implies that resilience metrics tie to grid and social adaptation measures, climate change metrics tie to grid and social mitigation measures, while health and social environment metrics’ ties are universal; they have ties with any and all categories of measures and environments.

- The cost and associated result/benefit of social mitigation and adaptation measures are hard to quantify. For many such measures, there is a non-linear and perhaps even non-convex function where the investment benefits taper off, or in other words, the learning curve flattens out. To complicate things further, a highly granular localization maybe be needed to accurately account for distinct social environments' and their reactions/ preferences and how these translate to measures' efficacy.

## Vulnerability assessment

Vulnerability assessment refers to the localization and ranking of system pain points. Within each climate change pace scenario, this step of the process comes up with a heat map of assets and electric grid locations that are more fragile than others. This pain point identification is highly granular; while metrics above were also described as granular, the granularity would be at a regional or local level, whereas for the pain point identification the granularity would be at the point of interconnection or electrical node.

We propose a mesh assessment of engineering and social indices. A list of pain points from an engineering point of view can be created by compiling lists of areas with aging equipment, areas with low or no capacity headroom, areas with expected fast demand increase (new loads for example from building or transportation electrification or load growth) or even areas with microclimates inducing particular stress.

A list of pain point from a health and social environment perspective can be similarly created; critical infrastructure, community fragility, asset's uniqueness etc can be the criteria.

Moreover, this step shall encompass a ranking of said pain points. This would attract investments towards the more critical issues to resolve, from a comprehensive engineering and social perspective. Sensitivity-based assessments can inform on the status of an asset given a climate event or system disturbance and allow ranking of pain points. Steps in this direction have been taken in the recent literature. In particular, PNNL has analytics to create fragility curves, creating the basis for relating the path of a hurricane to towers failing through a probability density function [13]. In the same open-source tool, PNNL maps critical facilities to neighbouring feeders supplying them. Improvements to the resilience of the feeder can thus be straightforwardly translated to improved availability/access to the facility.

Last but not least, a complete vulnerability assessment would also have a temporal element; a distressed asset at a time of no widespread system stress is much more manageable than an asset overloading during overall system high stress. On a parallel note, the temporal analysis is important for the vulnerability assessment since timeseries analysis is critical for assets whose lifetime is not solely dependent on clock time. For example, transformers' loss of life depends on their timeseries loading- low loading following high loading periods allow the transformer to cool down and have a more gradual loss of life than with more moderate but continuous/extended loading levels. Work in [14] investigated the impact of electrification and climate change on transformer's loss of life. While comprehensive 8760-hour time series analysis is the norm for transmission network and wholesale market analysis, it is yet commonly performed for distribution planning and analysis. Work in [15] proposed a highly granular evaluation of DERs as NWAs in the time and space domains. [16] followed a similar level of granularity to assess short-run costs of multi-product DER dispatch optimization.

## Investment prioritization

The core of the methodology is that for the outcome to be an all-around optimal, the policy should be decided through a comprehensive optimization problem that will collectively co-optimize climate change mitigation and adaptation solutions with a cost-minimization

objective. This formalization of the investment prioritization problem relies on establishing strong linkages between measures and metrics of interest through sensitivity-based metrics and formally quantified relationship functions. This is a gap in current literature and industry practices. Further, a climate/resilience plan should not be isolated from overall T&D planning; rather, T&D constraints should be considered as part of this investment prioritization. The investment prioritization is a multi-objective integer optimization problem that resembles a knapsack optimization problem logic. The following is a high-level sketch of the optimization logic:

$$\begin{aligned} & \min_x \sum_x b(x) \cdot cost(x) + CVaR(x) \\ & s. t. \sum_x b(x) \cdot cost(x) \leq B \quad (i) \\ & \quad metric_1 \leq target_1 \quad (ii) \\ & \quad \dots \\ & \quad metric_N \leq target_N \\ & \quad metric_1 = metric_1^0 + \frac{\partial metric_1}{\partial x} x \quad (iii) \\ & \quad \dots \\ & \quad metric_N = metric_N^0 + \frac{\partial metric_N}{\partial x} x \\ & \quad \bar{u} \leq f(x) \leq \underline{u} \quad (iv) \\ & \quad b(x) \in \{0,1\}, \forall x \end{aligned}$$

Where  $x$  is the evaluated solution,  $i$  is the subscript enumerating the relevant metrics,  $b(x)$  is the binary variable denoting the selection or not of solution  $x$ ,  $B$  is the total budget/max spend and  $a(i)$  is the monetization coefficient for metric “ $i$ ” (please see below).

The constraint set includes: (i) inequality constraints setting the summation of the cost of all selected solutions to be lower than a total budget/maximum spend limit that the interested party has available for climate change solutions, (ii) additional inequality constraints set upper thresholds for the defined metrics of interest. These constraints could restrict the value of a certain climate change metric to be below a selected target/threshold or it could be a time-coupled constraint that enforces a certain pace of improvement towards a target in a specific amount of time, (iii) additional equality constraints describing the change that solution  $x$  inflicts on each metric, and (iv) constraints imported from T&D planning.

This allows for higher valuation of solutions that address multiple concerns without double counting. The level of polishing and maturity of the above algorithm allows metrics used to be general in the network/area examined or to be specific, even down to the level of individual elements/assets.

The optimization is the minimization of overall costs; thus, the objective function consists of the cost of each solution, summed across all solutions, plus the conditional value at risk (CVaR). For each scenario, the CVaR is the cumulative expected consequence of an event quantified in terms of metrics (e.g., load not met, probabilities of assets failing). This risk-based cost assessment is more fitting to this concept of high-impact, low-frequency events. While more risk averse than a regular cost minimization, it also assumes a convoluted expectation calculation. The costs of implementing each solution are expected to naturally be in dollar terms. The metrics may not be monetized, hence a monetization coefficient shall be used.

## Conclusions and future work

This paper made the case for a quantitative, metrics-based climate plan investment prioritization, applicable to a wide spectrum of entities interested in climate plans and climate change solutions. A generalized formal optimization model was presented and the properties of the metrics needed were detailed. Future work includes the development of explicit mathematical relationships between solutions and metrics, the definition and consensus of more metrics, especially on the resilience metrics front, and potentially even more categories of metrics. Further, future work should ensure that the metrics shaping the investment are not interdependent, similar to how attributes used to classify clusters should all be independent. The penultimate step is a fully coordinated, comprehensive T&D planning with climate and resilience targets and investments.

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