

Climate Change Adaptation: Overarching Framework to Address Overlapping Industry Guidelines

Pouya Zangeneh¹, Navid Torkanfar², Sohiel Hassan³, Jason Jarrett⁴, Helen Adamson⁵, Predrag Jokovic⁶, Rafael Davilla⁷ and Stephanie Gangl⁸

1. Risk Analytics Specialist

2. Risk Analytics Specialist

3. Risk Analytics Specialist

4. Resilience Specialist

5. Senior Process Engineer Consultant

6. Managing Director of Engineering Development

7. Global Director, Tailings

8. Climate Change Specialist

Hatch, Mississauga, Canada

Corresponding author: Pouya.Zangeneh@Hatch.com

Abstract

From extreme weather events to changes in climate patterns, the adverse effects of climate change are felt across the world. Current scientific projections outline that, even withstanding international pledges to reduce emissions globally (i.e., climate change mitigation); the global mean temperature will increase by two to three degrees Celsius until 2100 (compared to pre-industrial mean temperatures). Addressing climate change acute and chronic physical risks, i.e., climate change adaptation, is becoming equally important as climate change mitigation, if not more, to create sustainable developments and operations. Determining when, how, and to what degree to adapt to climate change effects are questions of utmost importance and consequence. Complex transportation networks, water intensive operations, work force and geographical diverse communities, and intensive social and environmental permitting requirements are only some of the reasons for the long lived and capital-intensive mining operations to be vulnerable to adverse climate change effects.

Several industry bodies and authorities have devised pragmatic guidelines to tackle climate change adaptation for various industry sectors. These guidelines, however, often serve specific angles and therefore, utilize conflicting language and terminologies in conjunction appear conflicting with each other.

In this paper, we review the climate change adaptation challenges to the mining and metallurgical projects and industrial operations. We propose an overarching climate change adaptation framework to envelope various industry guidelines and practical engineering considerations and studies. We review the nature and scales of adaptive responses that must be understood before embarking on climate change adaptation journey. The proposed framework encompasses seven steps, starting from understanding the context, scope, and scale, and arriving at adaptation implementation.

Keywords: Climate change, Adaptation, Mitigation, Adaptive capacity, Sustainable development.

1. Climate Change in the Mining & Metallurgical Industries

In June and July of 2022, severe persistent heat waves developed across Europe with temperature anomalies leading to the highest recorded temperatures ever across the continent. Wildfires burned large swathes of lands across various counties. In France, an estimated total of 17 000

hectares were burned with more than 24 000 people evacuated. Overall, Europe recorded more than 5 000 heat related deaths, half of which from Spain alone. While the world is struggling to reduce greenhouse gas emissions to mitigate and prevent more climate change, the adverse effects of these changes are here, and the society needs to brace for them.

Weather and climate related hazards such as floods, hurricanes, extreme temperatures, and wildfires constitute about 90 % of all disasters [1]. At the same time, only 4 % of spending on disasters goes towards disaster prevention and preparedness, with 96 % spent on response, [2] painting a grim picture for the world that is anticipating more frequent adverse effects due to climate change.

The industrial complex of today has evolved drastically from yesteryear through increased optimization and reliance on limited resources. Particularly, the contemporary mining industry today utilizes complex transportation networks across large geographical spreads, operate climate and water sensitive processes, and maintain multinational work forces from diverse communities. Mining operations are required to maintain social license to operate and satisfy ever-increasing environmental permitting requirements. Mining industry with its long life and capital-intensive operations have become more vulnerable to adverse climate change effects. The International Council on Mining and Metals (ICMM) has conducted a review of its member organizations to gauge the materialized effects of climate change on mining operations and concluded no company or geography is immune of extreme weather and climate change [3].

To address these vulnerabilities to climate change, a growing number of industry bodies and authorities have devised pragmatic guidelines to tackle climate change adaptation for various industry sectors. These guidelines, however, are either vague and overly qualitative, or serve specific purposes and are tailored to specific sections of industries; they utilize conflicting languages and terminologies and hence are difficult for any organization to navigate and implement.

This paper review several of current industry related climate change adaptation guidelines and proposes an overarching climate change adaptation framework to envelope various industry guidelines and practical engineering considerations and studies. We review the nature and scales of adaptive responses that must be understood before embarking on climate change adaptation journey. The proposed framework encompasses seven steps, starting from understanding the context, scope, and scale, and arriving at adaptation implementation.

1.1 Climate Change Mitigation versus Adaptation

The terminology around climate change mitigation and adaptation can be used interchangeably in various contexts particularly when referring to climate change risks versus the climate change itself. However, most of the scientific literature when referring to the climate change itself utilize *mitigation* as to reduce carbon emissions to help prevent - more - global warming; while the *adaptation* is used to refer to adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

Figure 1 depicts the definitions of climate change mitigation and adaptation as in a causal risk diagram (bowtie). Climate change mitigation measures are aimed at reducing the organization's greenhouse gas emissions produced during their operations, utilized to generate the energy they import or in the way the organization's output is used. At the same time, climate change adaptations are those measures we take to accommodate to the climate change already being experienced or forecasted in the future.

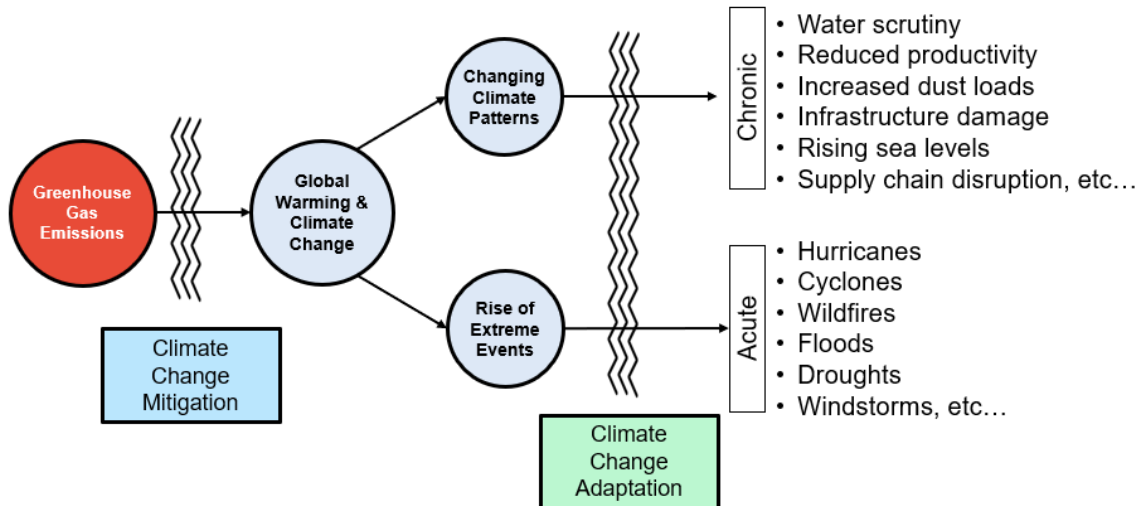


Figure 1. Difference between climate change mitigation and adaptation.

The balance between climate change mitigation and adaptation is the operating paradigm for organizations and industries at the present time, a need to ensure the reduction of emissions whilst learning how to adapt to the effects of emissions already made.

1.2 Drivers of Climate change Mitigation and Adaptation

As highlighted in the Intergovernmental Panel on Climate Change (IPCC) recent Sixth Assessment reports, some of the climate change impacts are irreversible [4]. It is also noted that both the public and private sectors are assessing their resilience and adaptation measures with increasing urgency in response to observed climate change and external stakeholder pressure.

In 2015, the Taskforce on Climate Related Financial Disclosures (TCFD) [5] was established by the G20 Financial Stability Board to provide guidelines to the public disclosure of climate-related financial information for the purposes of understanding a company's resilience to both the physical and economic changes brought about by climate change. Climate-related financial risk is described by the TCFD as both *transition risks* and *physical risks*, while the physical risks is divided to *acute* and *chronic* risks. Disclosure of this information is now mandated, or planned to be mandated, for publicly traded companies in many countries globally, and alongside with the rise of socially and environmentally aware investing and access to capital, are a few of the major driver of the climate change mitigation debate.

Nonetheless, the climate change adaptation efforts are derived by the sheer gravity of the vulnerabilities of the mining industry (and other industrial sectors) to climate change adverse effects.

How Much to Adapt

Considering the limits on resources available to react to climate change, the goal of any public or private organization is striking the balance in climate change mitigation and adaptation responses. The key question becomes how much adaption is needed, and what the optimized adaptive response looks like. These are hard questions to answer due to the general uncertainties involved in predicting the future climate change scenarios.

Another important aspect in answering these questions is the agency of private agents in adaptation to climate change. While the climate change mitigation is mainly enforced by the world

citizens, climate safeguarding organizations, and financial markets on the industries, it would require a collective global response and it goes against any single agent utility to individually reduce its carbon emission. However, the physical and transitional risks of climate change affect the bottom lines of each individual business (game theoretic agents) directly and hence, provide enough incentive for them to pursue climate change adaptation.

Several other important considerations are *adaptive capacity* and *impact severity*. Adaptive capacity is the inherent ability of the agent to avoid damages due to changing conditions, while the impact severity depends on characteristics of extrinsic changing conditions [6]. Put in the climate change context, the two will have an inverse relationship while governing the right balance between climate change mitigation and adaptation. Most importantly, increasing adaptive capacity itself can be considered a form of climate change adaptation. Figure 2 outlines possible tradeoffs between adaptive capacity and impact severity within the context of the climate change adaptation and mitigation costs.

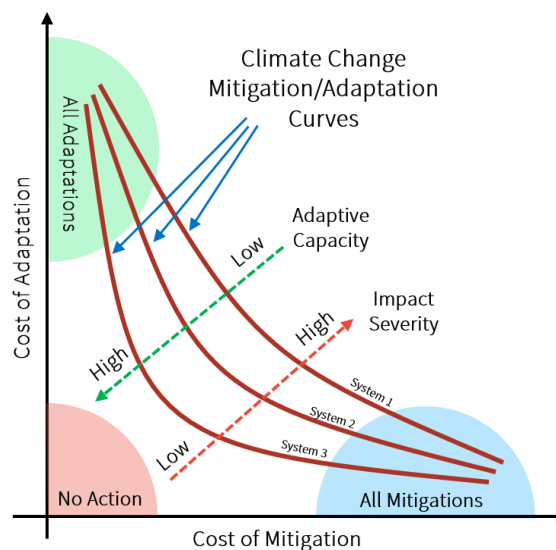


Figure 2. Inverse relationship of Adaptive Capacity and Impacts Severity within the necessary mix of Climate Change Mitigation and Adaptation.

1.3 Climate Models

Climate models are used by scientists to reproduce ocean water circulation, seasonal annual cycles, and the flow of carbon among the atmosphere, land surface, and oceans by taking the fundamental physical equations of the Earth’s climate variables as inputs.

Development of computerized climate modeling was accelerated after the second world war with the first milestone being a successful weather forecast by a group of New Jersey meteorologists in 1950 using numerical prediction techniques. This type of modeling has evolved significantly over time; the scientists today use massive supercomputers with enormous computing power to simulate climate models. The main input category into climate models are external factors (“forcings”), that influence the amount of the sun’s energy absorbed by the Earth or trapped in the atmosphere. Examples of these forcings are the sun’s varying radiation output, variable atmospheric concentrations of greenhouse gasses (GHG, for example CO₂, CH₄, N₂O) or aerosols (particles emitted by processes such as fossil fuel burning and volcanic eruptions which influence sunlight and cloud formation). Past forcings can be estimated by reconstructing greenhouse gas concentrations (e.g., by analyzing air trapped in ice cores), climate gas and particle emissions

during past volcanic eruptions, or changes in the Earth's orbit (i.e., cyclical variations in solar radiation reaching the Earth due to Milankovitch cycles).

Climate models are continuously being updated. The updates are resulting from contributions of scientific modelling groups around the world which refine spatial resolution or simulate new physical processes and biochemical cycles. These coordinated efforts are part of the Coupled Model Intercomparison Projects (CMIP); the latest being CMIP6 used in production of the IPCC Sixth Assessment Report (AR6) in 2021 [4]. The different models combined within CMIP are all given common set of scenarios (concentrations of GHGs, aerosols and other various forcings) in order to allow for their outcome comparison. The scenarios used in creating CMIP6 reflect on various socio-economic drivers (e.g., future developments in society, technology, energy, and land use) and are called "Shared Socioeconomic Pathways" (SSPs).

The models produce various categories of output. The main outputs of a climate model are temperatures and humidity of different atmospheric layers, estimates of ocean temperatures, salinity, and acidity from the surface to the seafloor as well as snowfall, rainfall, snow cover and the extent of glaciers, ice sheets and sea ice. They also provide information about wind speed, strength, and direction, as well as other climate features, such as the jet stream and ocean currents.

2. Climate Change Adaptation Challenges

2.1 Types of Adaptation

Throughout time, societies and individuals adapted to changes in weather conditions from year to year, especially in the agriculture sector due to the direct impact on yields. These changes were often of a gradual and intuitive nature that did not require any intensive planning or resource reallocation. On the other hand, another strategy to adapt to climate change is through strategic planning that leads to major shifts in operations and workflows to account for both current climate change effects and predicted future risks. Park et al. [7] discussed this concept further by dividing adaptation strategies into *incremental* and *transformational* adaptations depending on whether the key fundamental aspects of the process at hand are modified or not. As companies adopt more transformational adaptation methods over incremental adaptation, the associated risks, complexities, and costs increase but they can reap more sustainable benefits in return.

2.2 Scale of Adaptation Planning

Identifying the scale of climate change adaptation planning is of utmost importance in creating a proper adaptation road map. The scale of planning mainly depends on three aspects of the climate change adaptation study project as schematically shown in Figure 3. The first aspect is the decision-making objective of the adaptation study, its impact and its importance. As the decision becomes more instrumental, the scale of the study is increased to account for as many factors as possible to reduce uncertainties.

The second aspect is the maturity and the process stage of the adaptation study; during the initial planning stages, the study can be conducted at a smaller scale, and then can gradually become more rigorous as the project progresses [8].

Third, while the scale of planning depends on the stage of the project and study objectives, the type of study choice between quantitative and qualitative analysis depends on the type of information available. Depending on the climate risk being assessed, and the stage of the project, the degree by which quantitative data is available will differ. When sufficient data is not available, a qualitative analysis to identify the risks can highlight areas where more data collection is necessary. However, a semi-quantitative analysis by assigning relative scores and ranking the

risks or adaptation strategies might still be needed to allow for more streamlined decision-making process and better communication with the stakeholders. Ultimately, for the purposes of analytics and detailed assessment, fully quantitative studies might be necessary for highly consequential decisions and where relevant information is available.

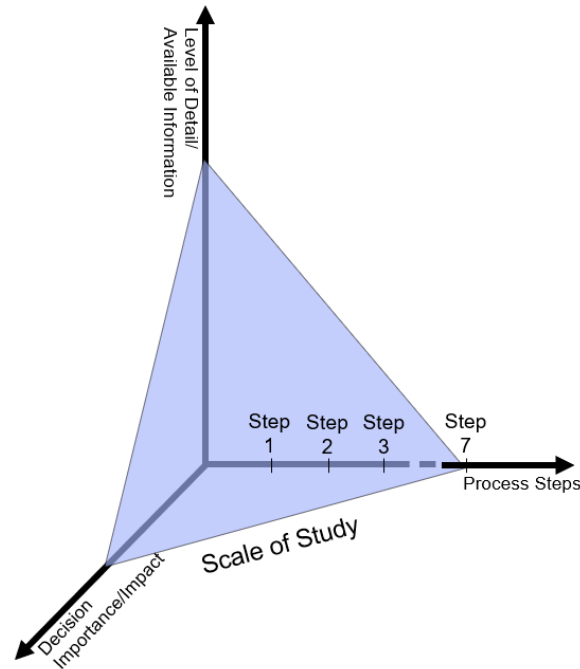


Figure 3. The schematic relationship between project process step, decision importance, and level of available information in forming the scale of the study

As with most tasks of project planning and assessment, climate change adaptation planning is an iterative process that should be consistently revisited and improved upon as more information becomes available. This is especially applicable to climate change as planning decisions are based on predicted events and expected risks, and so as the scenarios materialize over time, the actualized information should be used to improve planned responses for future events.

3. Industry Guidelines

The following sections review several most important guidelines that are studied and considered in proposing the framework in this paper. The guidelines provided by the International Council of Mining and Metals (ICMM) and the Mining Association of Canada (MAC) are used as foundations for the proposed framework as they are considered among the most accepted publicly available frameworks.

3.1 International Council of Mining and Metals (ICMM)

The International Council of Mining and Metals (ICMM) is a major international mining body composed of several mining companies. It is a vehicle for spreading best practice and standards and as such is committed to improving sustainable development and meeting societal needs of the industry. With a clearly articulated goal of environmental resilience, ICMM developed a seven-step continuum to identify climate risks, mitigate their impacts and where possible, adapt to them accordingly. At a high-level, the process relies on identifying the unique circumstances of each project and the future climate risks it may be vulnerable to. It includes understanding the impacts of such risks and evaluating different adaptation pathways available to develop a path forward [3]. Table 1 summarizes the ICMM climate change adaptation guidelines.

3.2 Mining Association of Canada (MAC)

The Mining Association of Canada (MAC) has been collaborating with provincial governments regarding any policies that impact the mining industry and has been promoting the sector at both national and international levels. In order to address the concerns of various communities of interest, MAC released a guide for climate change adaptation that consists of a three-step process: climate risk assessment, developing adaptation pathways, and implementing adaptation pathways. The guide relies on an iterative process to account for future climate risks in different components of the project site, assess the different adaptation options based on their outcomes, and implement the selected pathways [8]. Table 1 summarizes the MAC climate change adaptation guidelines.

3.3 Climate Lens and Public Infrastructure Engineering Vulnerability Committee (PIEVC)

Infrastructure Canada has created publicly available requirements for considering climate change risks and impacts to be used in infrastructure investments and disaster mitigation decisions. These guidelines, collectively referred to as Climate Lens, include two components of GHG mitigation assessment, as well as the climate change resilience assessment. As described by the Infrastructure Canada, Climate Lens “employs a risk management approach to anticipate, prevent, withstand, respond to, and recover and adapt from climate change related disruptions or impacts.” The Climate Lens recommends few methodologies to assess the climate change risks, particularly among those methodologies is the one developed by the Public Infrastructure Engineering Vulnerability Committee (PIEVC). PIEVC was initiated by Engineers Canada, with support from Natural Resources Canada, and developed a protocol targeted at public infrastructure projects to allow engineers to account for climate change impacts. The PIEVC Protocol involves a five-step process to evaluate climate risks and develop recommended adaptations. The process places more emphasis on the identification and scoring of climate risks based on their likelihood and severity, and less emphasis on the evaluation of different adaptation methods for the identified risks [9].

3.4 International Organization for Standardization (ISO)

The International Organization for Standardization created a set of guidelines and principles for different organizations to abide with when it comes to climate change adaptation planning. The guidelines provide a high-level framework of the climate change adaptation plan including identification, assessment, and adoption of potential adaptation actions, and developing adaptive capacity. The ISO guidelines also emphasize the need to identify organizational objectives and rationale as well as documenting relevant decisions that should account for levels of acceptable risk and the appropriate strategies for the involved organization. Unlike other guidelines that provide linear and iterative steps to follow, the ISO plan provides a list of different outcomes and considerations that the adaptation plan should account for [10].

3.5 World Bank Group (WB)

The World Bank Group created an action plan at the country level for climate change adaptation and resiliency that identifies different ways to address climate change adaptation barriers at a national and global level. The WB framework also focuses on developing a data-driven plan that involves climate risk analysis and stakeholder involvement. In addition to that, the plan identifies cross-governmental and cross-country coordination as an important principle to increase policy and plan effectiveness [11].

4. Proposed Seven Step Overarching Methodology

The mining complex of today requires complex transportation networks, water intensive operations as well as multinational work forces and operations in geographically diverse communities. In addition, modern mining needs to satisfy intensive social and environmental permitting requirements, both of which are among the many fault lines making long life and capital-intensive mining operations vulnerable to adverse climate change effects [3]. As a result, climate change adaptation is a critical step in creating sustainable developments and operations.

It is clearly in the interests of the industry to prepare for climate change by sharing expertise and experience. This is reflected in the growing number of industry bodies and authorities, such as ICMM and MAC that devised pragmatic guidelines to tackle climate change adaptation for various industry sectors.

This paper proposes a seven-step protocol for conducting climate change resiliency assessment and adaptation planning which is developed based on such leading industry guidelines. The proposed framework and its alignment with ICMM and MAC guidelines are summarized in Table 1.

The proposed framework includes seven steps as similar to the ICMM guidelines, however, is aimed to increase specificity and better describe the nature of the involved activities. This framework has resulted from consultation with various subject matter experts to clearly articulate the scope and create discrete yet connected and flexible engineering work packages. These steps are discussed in detail in following sections.

Table 1: Seven-step proposed methodology for climate change adaptation campaigns.

Steps	1	2	3	4	5	6	7
Proposed Protocol	Scope and Scale Definition	Climate Modeling and Hazard Assessment	Exposure and Interdependencies Assessment	Risk, Vulnerability and Opportunities Assessment	Climate Adaptation Recommendations & Pathways	Cost Benefit Analysis	Climate Change Adaptation Implementation
Alignment with industry proposed methodologies							
ICMM International Council on Mining and Metals	Defining the scope	Exploring future climate scenarios	Understanding the current situation	Assessing climate risk and opportunities	Identifying risk management / adaptation pathways	Evaluating risk management / adaptation options	Develop and implement adaptation pathways
MAC Mining Association of Canada	Stage 1				Stage 2		Stage 3
	Climate Risk Assessment				Developing Adaptation Pathways		Implementing Adaptation Pathways

4.1 Scope and Scale Definition

The first step in climate change resiliency assessment and adaptation planning is a comprehensive joint exercise with all project stakeholders to establish the scope and the scale required. Scope and scale definition is intended to improve the project’s chances of success by understanding the resources and the capacity of the organization within the broader context of the organization’s operations and current initiatives. Based on the organization’s previous and existing efforts the team sets the narrative for an overarching climate change adaptation approach and makes fine adjustments to strengthen the organization’s own internal functions.

The appropriate information sharing channels are also established during this stage and the information required for the project is shared and reviewed by the project team. By articulating the scope, the team establishes the scale of analysis required to achieve the project goals, and proper initiation process for further focused technical studies. Eventually, a road map for the work will be created.

4.2 Climate Modeling and Hazard Assessment

To embark on a sustainable climate modeling the first step is to agree on a common source of climate related data including physical, biogeochemical, biological and land-based variables. This involves compiling and analyzing existing data to develop future climate projections for the operations covered by the scope. To generate future projections, existing historical datasets need to be cross validated with the best available data applied for the analysis such as CMIP6 Earth System Model (ESM) data and the SSP emissions scenarios [4].

4.3 Hazard Screening and Combinations

Depending on the necessity, flood modelling or other secondary hazard assessments will be carried out to arrive at hazard maps and descriptions, such as flood inundation maps, or hazard description to industrial plants, infrastructure, and other strategic assets. For this purpose, a register listing potential climate change hazards should be maintained. As a regular agenda item for progress meetings, this register of hazards will develop and improve over time. Table 2 depicts a high-level example of a climate change hazard screening register.

The interrelations between hazards can create complex, compounded, and concurrent effects. As a result, understanding and identifying the interrelations between natural hazards that may give rise to multi-hazards or hazard combinations is of utmost importance. This is especially true for unknown confounding effects that climate change may induce over current hazard levels.

In analyzing hazard combinations, it is necessary to have extensive knowledge of the company operations, risk thresholds and regulatory environment; hence, the credibility of this step builds on the experience of the subject matter experts as well as the working knowledge of the site and operations. Table shows a high-level example of multi-hazard combinations and possible hazard interrelations.

These interrelations may be categorized into five types [12]:

1. Independence: Hazards are independent, although coincidences may occur. An example of an independent combination is the 2010 Pacaya volcanic eruption and tropical storm Agatha which hit the Pacific coastline of Guatemala almost simultaneously.
2. Triggering: Primary hazards lead to secondary hazards and so on. A triggering combination example is where an earthquake might trigger landslides, which can trigger a flood, resulting in cascading hazards.
3. Change condition: Hazard alters the disposition of another hazard by changing environmental conditions. An example of a change condition combination is when a wildfire changes soil infiltration up to one year after its occurrence leading to an increased flood level. This happened in Las Conchas in New Mexico in 2011.
4. Compound hazard: Same primary hazard may manifest through different channels and a more significant scale effect. For instance, co-occurring river flooding and sea level surge that may result from the same multi-hazard large-scale process such as a tropical cyclone.
5. Mutual exclusion: Hazards are negatively dependent to the point of mutual exclusion. For example, extreme rainfall and wildfires are not likely to simultaneously occur.

Hazard combinations will be investigated by subject matter experts and reviewed and modified within workshop settings. Table 3 shows a high-level example of multi-hazard combinations and possible hazard interrelations.

Table 2. Sample Eliciting, and screening various hazards to the operations and the operations’ adaptive capacities.

Climate Hazard	Trend	Relevance	Potential Impacts	Adaptive Capacity	Potential Risks
Temperature	Increasing	Yes	The efficiency of thermal power generation may be reduced by higher air temperatures	Operational changes, such as increased maintenance, that could reduce the vulnerability of infrastructure to climate variability and extremes.	MODERATE
Extreme precipitation and flooding	Increasing	Yes	Hydropower plants are highly sensitive to climate-induced changes in water levels which may be caused by changes in temperatures and rainfall	Planning for redundancy and options that could accommodate disruptions in service due to natural disasters and changing climatic conditions.	HIGH
Strong winds	Increasing	Yes	LOW
Droughts	Decreasing	No	NO RISK
...

Table 3. Sample Eliciting and representing hazard combinations.

Precipitation				
Strong Winds	Compound hazard			
Extreme Temperatures	Mutual exclusion	Independence		
Flooding	Triggering	Compound hazard	Independence	
	Precipitation	Strong Winds	Extreme Temperatures	Flooding

4.4 Exposure and Interdependencies Assessment

The process of understanding incidents’ impacts on the organization and its surrounding communities, begins with an Exposure and Interdependency Assessment. This is initiated by compilation of a detailed list of the assets within scope, the infrastructures operated or not operated by the organization, GIS locations as well as functional descriptions and operational details. Each fact gathered can be mapped in relation to others and graphically represented as a point of information on a map. Such a data construct would capture key inputs and outputs, dependencies and timeframes, making it possible to understand where practical changes can be

made to have the greatest effect. Such a web of dependencies can be queried to better understand the interdependencies between the different factors.

An important consideration in understanding the interdependencies of any operation is distinguishing between the internal and external operational dependencies. The internal dependencies within a plant are identified at a high level within the process flow diagram. These dependencies should be pinned to the geographical locations as part of exposure assessment. The external operational dependencies are where the operations rely on other stakeholders and authorities for their management, availability, and maintenance. Examples of external dependencies are roads, railways, and ports.

4.5 Risk and Vulnerability Assessment

The goal of this step is to identify and assess the likelihood and consequence of risks and vulnerabilities to climate change induced hazards, which is founded based on the Exposure and Interdependency Assessment conducted in the previous step. This step will identify critical vulnerabilities as well as potential direct and indirect impacts on the organizations' plants and infrastructure necessary to deliver their business-critical activities.

The risk and vulnerability assessment is conducted considering several important impacts, including, but not limited to, operations, ecosystems, assets maintenance and importantly, health and safety, and community impacts. The exposures and interdependencies assessment highlights various climate change impacts and opportunities. To understand impacts of climate change on the organisation it is important to consider several different factors, including:

- How local geography interacts with the current climate.
- The projected future climate for the next forty years or other predetermined timeframes for consideration.
- The arrangement and layout of the infrastructure and the assets in scope
- How current risks are being managed and how they might be impacted, for better or worse, by climate change.

It is important to note that both the exposure and the vulnerability profiles of an organization will change over time, in terms of assets' life cycle, and the climate change trajectories. Therefore, it is important to create live risk registers, data collection systems, and dashboards to capture these changes and strengthen the organization as their climate change adaptations unfold.

The risk and vulnerability assessments exercise might happen through semi-quantitative workshops between the organization, their key suppliers, and other stakeholders' technical leads. The effectiveness of the risk and vulnerability workshops process can sometimes be impacted by a variety of "human factors". Experienced risk management workshop facilitators need to navigate highly technical discussions and to create collaborative sessions where all participants express their opinion.

Where applicable, the workshop planners will ask workshop participants to complete relevant questionnaires to establish independent starting points for the conversations (Delphi method) [13] and as well to increase the collaborative output and commitment of the participants during the workshop sessions. These independent individual assessments provide a baseline to evaluate the risks from a multitude of perspectives that is free from anchoring and possible group-think heuristics.

4.6 Climate Change Adaptation Recommendations and Pathways

With major climate change induced risks and vulnerabilities of the operations identified, the next goal is to develop conceptual designs and strategic options to mitigate, prevent, or avoid impacts to the operations. These will form the basis for climate change adaptation recommendations.

For many of the identified risks and vulnerabilities, it is likely that an organization already has controls and mechanisms in place. However, the dynamic nature of climate change and the uncertainty around it will cause new challenges, and moreover, new risks and vulnerabilities may manifest. The correct and most appropriate solution for today may no longer be relevant in the next decade, let alone the next forty years, as climate changes continue to impact the same said solution, perhaps rendering it no longer fit for purpose. Therefore, any resulting solution should consider both current and possible future impact and ideally be flexible to accommodate potential future unforeseen changes. To inform the remaining steps of the planning process the adaptation pathways need to consider implementation of measures over the short, medium, and long term.

Developing adaptation pathways will enable an organization to have an approach to adaptation planning in this uncertain environment. Such pathways are essential for evaluating, developing, and implementing adaptations while considering multiple possible future scenarios.

Adaptation measures are actions taken to manage an organization's climate change risks or opportunities associated with their assets and infrastructure serving them. They should be engineered to take advantage of any opportunity, reduce the residual risk to an acceptable level, mitigate the consequences of an adverse impact or ideally eliminate the climate change risks and vulnerabilities by design.

Examples of climate change adaptation actions may include constructing new infrastructure capable of handling projected climate change, allocating strategic investments accordingly, as well as developing and maintaining future climate change projections.

4.7 Cost Benefit Analysis

With having a comprehensive understanding of hazards, operations' exposure to hazards, major risks and vulnerabilities, and adaptation recommendations, this step focuses on utilizing decision analysis tools to evaluate and select the potential adaptation pathways. The developed adaptation pathways are to support strategic, flexible, and structured decision making which allows for planning and prioritizing necessary CAPEX investments. In doing so, the project team shall prepare a preliminary cost estimate (e.g., according to the Association for the Advancement of Cost Engineering (AACE class 5) [14]) for major design requirement items proposed within climate change adaptation recommendations and pathways. The cost estimate can be further developed with higher accuracy at different scales and stages of the project.

In principle, any investment on climate change adaption pathways should be assessed based on demonstrable return on investment (ROI). The ROI is established based the Loss Avoided as defined in Equation (1) [9].

$$\mathbf{Loss\ Avoided\ (\$)} = \mathbf{LOSS}_{adaptation\ project\ absent} - \mathbf{LOSS}_{adaptation\ project\ complete} \quad (1)$$

The ROI can then be calculated as the percentage of the project cost as seen in Equation (2).

$$\mathbf{ROI\ (\%)} = \frac{\mathbf{Loss\ Avoided}}{\mathbf{Project\ Cost}} \quad (2)$$

With major climate change induced risks and vulnerabilities of the operations identified, preliminary cost benefit analysis or the bounding analysis underlining the limits of potential variabilities of future climate projections, the next goal is to incorporate the study results into the design criteria, or implementation plans.

4.8 Climate Change Adaptation Implementation

Climate change adaptation implementation consist of several distinct phases. It commences with conceptual development followed by prefeasibility and feasibility studies. This sequence signifies increasing level of project/engineering definition and cost estimate accuracy. Feasibility level study usually results in the budget authorization and initiation of detail engineering of the proposed solution. Completion of detail engineering is a precursor to the project procurement and construction activities.

Each phase requires set-up, planning, execution, and control. Planning and set-up consist of developing work plans as well as establishing baselines and project team structure. Execution and control are focused on the target deliverables scope, quality, and schedule. The project plans are implemented and maintained while scope and/or schedule changes are managed.

As with other engineering implementation projects, for climate change adaptation it is very important to understand and meet all stakeholder expectation from a delivery standpoint.

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