High-level Climate Change Risk Assessment (*CCRA*) for Paardevlei PV Plant - South Africa

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Parc Barcelona Activa
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Prepared by: Ana López and Patricia Darez
Reviewed by: Gil Lizcano

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Executive Summary

Climate change can have both positive and negative impacts on solar PV production, through changes in solar insolation and air temperature that might directly affect production, and through more intense or frequent extreme events that could disable or destroy PV infrastructure that is not designed accordingly.

This Climate Change Risk Assessment presents a high-level summary of the observed variability and the projected changes under different emissions scenarios, for the key climate drivers of impacts on the PV solar production and supporting energy infrastructure in the Paardevlei PV Plant area. Based on this information, the physical risks and opportunities posed by climate change to the solar PV plant project are identified, and high-level recommendations for mitigation options are proposed where relevant.

Risks associated with changes in temperature, precipitation, solar irradiation and wind patterns over the next 40 years are estimated using CMIP6 global climate models downscaled to the location of the project. Uncertainties in climate model projections are taken into account by considering an ensemble of climate models and three emissions scenarios: SSP2-4.5, SSP3-7.0 and SSP5-8.5, and using these data to assign a level of confidence to the projected risks.

Based on these modelling studies:

- Temperature related metrics (mean air temperature, heat waves, human felt temperature) show robust positive changes with high confidence in the projected changes for all scenarios.
- Mean precipitation is projected to decrease and droughts are projected to increase (high confidence in the mid term), while extreme precipitation is projected to increase (high confidence).
- Projected changes in mean global and diffuse horizontal irradiance are small (less than 1%) and there is nor robust signal in the direction of changeover the next 40 years.

The physical risks analysed that could affect the infrastructure and operation of energy systems include extreme Heat stress (for humans), extreme Fire Conditions (wildfires), extreme precipitation (as a proxy for surface and pluvial flooding), water scarcity (droughts), extreme wind (storminess) and hail storms, coastal inundation and erosion.

Specific risks associated with acute and chronic hazards relevant for solar PV technologies are also considered, including secular changes in mean Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI), and increases in air temperature, extreme heat and wind reductions that could affect the efficiency of the panels and other components.

> High risks of wildfires and water scarcity are identified during the historical period and over the next 40 years. No high levels of risks are identified for solar PV specific metrics, including for changes in irradiation that could affect the resource.

Recommendations for mitigation measures to address the high risk of wildfires and water scarcity are discussed. In the case of hazards where high risks are not identified, the recommendations provided are aimed at building in climate resilience. This is particularly important in cases where the confidence in the projected risks is not high, since this indicates that at present, there is not a robust climate change signal across climate models.

Continuous monitoring of the environmental conditions in the future, and the analysis of new climate information as it becomes available are recommended. This data can be used to compare conditions and performance throughout the life of the project, and revise and adjust mitigation measures if necessary.

The impact of decommissioning and disposal of the power plant and its components is also discussed. Disposing and recycling of the components of the plants is an area that is still developing and although successful policies have been implemented in more mature markets, South Africa will also need to implement suitable regulation to ensure recycling facilities are available locally. If this implementation is successful in the next 20 to 30 years, the risks of sending the components to landfill or environmental liability will be small and manageable. Even if this is the case, it is recommended that a budget is set apart to ensure a successful decommissioning phase including the recycling of the plant's components, as is currently done in other markets such as the EU or Australia.

1- Introduction

Climate change can have both positive and negative impacts on solar PV production. While it is not expected to significantly affect solar insolation, increases in temperature due to anthropogenic climate change can decrease solar power output by reducing PV panel efficiency. Changes in cloud formation can also affect global solar irradiation and therefore affect solar production locally. In addition, events such as floods, tropical cyclones, extreme temperatures, and wildfires pose and increase risk to energy infrastructure around the world. These adverse weather events are increasing in frequency, intensity, and variability posing the risk to disrupt, disable or destroy PV infrastructure that is not designed accordingly.

According to the City of Cape Town Climate Change strategy (City of Cape Town, 2021) the climatic changes that the city faces include significant decrease in annual rainfall, increases in mean temperature and more frequent and intense heat waves, increase in mean sea level and coastal erosion.

This Climate Change Risk Assessment presents a high-level summary of the observed variability and the projected changes under different emissions scenarios, for the key climate drivers of impacts (or physical hazards) on the PV solar production and supporting energy infrastructure in the Paardevlei PV Plant area. Based on this information, the physical risks and opportunities posed by climate change to the project are identified, and high-level recommendations for mitigation options are proposed where relevant.

The physical hazards selected follow the EU Taxonomy[1] climate-related hazards classification (*table 1*), as a recognised international standard to map physical impacts of climate change on economic activities. This includes the metrics that are potentially relevant to analyse how climate variability and change might affect the PV plant's energy potential, its design, and future operations and maintenance. The distinction between chronic and acute hazards follows the Task Force on Climate-related Financial Disclosures (TCFD)[2] recommendations for the disclosure of climate change physical risks.

[1] COMMISSION DELEGATED REGULATION (EU) 2021/2139 of 4 June 2021. http://data.europa.eu/eli/reg_del/2021/2139/oj [accessed 27-04-2022]

[2] The Task Force on Climate-related Financial Disclosures (TCFD) was created to improve and increase reporting of climate-related financial information.

EU Taxonomy climate-related hazards Classification				
	Temperature-related	Wind-related	Water-related	Solid mass-related
Chronic	Changing temperature (air)	Changing wind patterns	Changing precipitation patterns and types (rain, hail, snow/ice)	Coastal erosion
	Heat stress		Precipitation or hydrological variability	Soil degradation
	Temperature variability		Ocean acidification	Soil erosion
	Permafrost thawing		Salinity changes	Solifluction
			Sea level rise	
			Water stress	
Acute	Heat waves	Cyclone, hurricane, typhoon	Drought	Avalanche
	Cold waves/frost	Storm (including blizzards, dust and sandstorms)	Heavy precipitation (rain, hail, snow/ice)	Landslide
	Wildfire	Tornado	Flood (coastal, fluvial, pluvial, ground water)	Subsidence
			Glacial lake outburst	

Table 1: Classification of climate related hazards according to the EU-Taxonomy. Colours indicate hazards analysed in this report. Source: adapted from EU Taxonomy of Sustainable Activities Annex 1.

Some of the metrics in table 1 are not considered hazards due to the location of the project (i.e., permafrost thawing, tornadoes, glacial lake outburst). Temperature, water and wind related metrics, together with solar irradiation, are analysed for the historical period (2000-2019 unless otherwise stated), and two projection periods (2020-2039 and 2040-2059). Assuming a lifetime of between 20 and 30 years, these periods cover the expected lifetime of the project. Solid mass related risks including landslides, soil erosion, and subsidence are reported only for the historical period.

Projections of the impacts of anthropogenic climate change on the different climate metrics are obtained by statistically downscaling a CMIP6 ensemble of climate models, for emission scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5 respectively.

Based on the Climate Science literature (IPCC, 2021) the term ‘physical climate risk’ can be conceptualised as the combination of the potentially damaging physical event or hazard (e.g., flood), the exposure of people or assets to these variations (e.g., assets built in flood prone areas), and their vulnerability (e.g., no flood protection measures). Due to the lack of detailed information about the different components of the project, the physical risks identified in this report refer only to the hazard component of the risk. Unless otherwise stated, vulnerability and exposure of the assets are not taken into account when assigning the risk levels (section 4).

This report is organised as follows:

- **Section 2** identifies the climate drivers of impacts on energy infrastructure and PV solar technology, drawing from relevant information from IPCC Sixth Assessment Reports [IPCC 2021, IPCC 2022], together with other scientific literature, and feedback from experts.
- **Section 3** includes a discussion of the localised observed and projected climate at the project area. Both, changes in extreme events (acute changes), and secular or chronic changes are considered.
- **Section 4** identifies the risks and opportunities projected for the site, considering general energy infrastructure such as transmission lines and substations, as well as specific risks affecting PV solar.
- **Section 5** discusses the impact of decommissioning and disposal of the power plant and its components.
- **Section 6** summarises the results including recommendations and proposed high level adaptation options
- **Appendix A** describes in detail the data and approach used to derive climate hazards and risk, and their definitions.
- **Appendix B** describes physical risks and their definitions.
- References to abbreviations are defined in the Glossary in **Appendix C**.

2. Identification of potential impacts of climate change on solar technologies and its climate drivers

Climate change has direct and indirect impacts on energy systems. The direct impacts on energy systems includes development, transportation and supply for instance, but also energy demand, increasing the energy consumption for cooling in summer and decreasing the need for heating in winter. Higher demand for cooling due to hotter temperatures has become a major challenge in the energy sector in all countries.
In the case of renewable technologies such as solar PV and wind, where resources are strongly dependent on weather, climate change can potentially impact the supply.
In addition, extreme weather events could generate major damage to power plants, as well as power transmission towers and lines.
In this section, the climate drivers of these impacts on solar technology and energy infrastructure are identified based on information drawn from the IPCC Working Groups I and II Sixth Assessment Reports [IPCC 2021, IPCC 2022], other scientific literature, and feedback from experts on the different technologies.

2.1 Solar PV technologies

Climate change impacts solar PV production through changes in temperature, insolation and cloudiness. Changes in insolation and cloudiness are the main effects on the resource base for all types of solar energy: solar heating, photovoltaic and concentrated solar power. Increasing cloudiness will reduce output from photovoltaics.
Increasing temperatures decrease the efficiency of photovoltaic panels, and deposition and abrasive effects of wind-blown sand and dust on solar energy plants can further reduce power output, and increase the need for cleaning.

Existing literature focuses mainly on changes in solar irradiation, as it is the most relevant source of impacts. The other variables are usually mentioned but not quantified, which may lead to an underestimation of their importance. Most papers focus on impacts on the resource, without quantifying changes in production or the economic impacts [Solaun 2019]. Table 2 summarises the climate drivers of impacts on the resource and operations, maintenance and infrastructure of PV solar generation in general [Solaun et al 2019, IEA 2019, IPCC 2022, Yalew 2020]. In the following section the impacts of climate change will be analysed only for the drivers relevant for the location of the project.

Climate Drivers	Potential Impacts on Resource	Potential Impacts on Infrastructures and O&M
changes in mean temperature	Affects efficiency of panels and consequently power output. Efficiency is estimated to drop 0.35% to 0.45% per °C increase depending on the module and manufacturer type.	Might affect operational costs. Long term exposure to higher temperatures causes faster ageing of sensitive material.
extreme high temperatures	Negative impact due to reduced power output.	Material damage to PV equipment.
wildfires		Material damage to PV equipment.
changes in mean precipitation	An increase could be positive through washing away dust, but negative due to a rise in cloudiness.	
extreme precipitation storms hailstorms		Impacts on integrity of panels. Damage to PV infrastructure. Lightning can damage the inverter in photovoltaic panels.
flooding (riverine, pluvial, coastal, ground water)		Damage to PV infrastructure.
meteorological drought		Impacts on water availability for cleaning PVs, creating conflicting priorities.
change in might wind speed	Changes might affect production (increasing if wind increases, through cooling effect).	
extreme winds		Impacts on integrity of panels, mounting and fixing. Strong wind might cause material damage to PV infrastructure, and need for cleaning (due to sand and dust deposition).
changes in global and diffuse horizontal irradiance	Direct impacts on resources. Changes affect power output.	
changes in dirt, dust, snow, atmospheric particles	An increase could decrease power output.	Increases in dust and sand storms might increase the need for water for cleaning.
sea level rise		Increased exposure to coastal flooding, storm surge and inundation

Table 2: Climate drivers of impacts on the resource and operations, maintenance and infrastructure of PV generation [Sources: Solaun 2019, IEA 2019, IPCC 2022, Yalew 2020,GCF 2023].

2.2 Energy infrastructure

While the drivers discussed in the previous subsections affect specific technologies, the ones listed in Table 3 can affect energy infrastructure in general, including supporting infrastructure such as substations and transmission lines.

Climate drivers	Potential impacts on infrastructure, and O&M
Heat stress	Substations: Prolonged exposure to high heat could cause accelerated degradation of the asset and earlier than expected retirement. Capacity issues may arise from combined asset derating with increased demand from heat.
Wildfires	Material damage to any type of equipment.
Flooding	Transmission: Rapidly moving water could cause washed out at the base of the structure Substations: Floods can cause failure in control cabinets, fans, pumps, causing indirect failure in the transformer Distribution poles: Fast moving water could cause erosion and impact pole foundations
Extreme wind (storms, tropical cyclones)	Transmission: Extreme winds can result in total structure failure or collapse Distribution poles: Extreme wind could cause the poles to fall over or break

Table 3: *Climate drivers of impacts on the resource and operations, maintenance and infrastructure of energy infrastructure.*

3. Observed climate and future projections

3.1 Site information

The Paardevlei PV Plant is located in South Africa (lat 34°04'16", long 018°47'53") to the East southeast of Cape Town

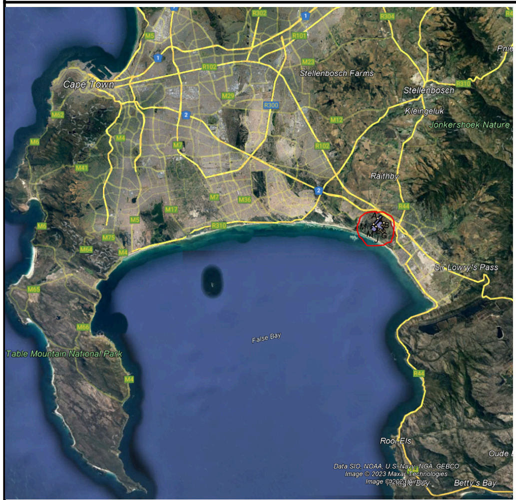
Wider context with relation to Cape Town	***Affected Areas (38ha+80ha+34ha)***
	

Figure 1:location of the Paardevlei PV Plant . The latitude and longitude where downscaled climate data was calculated is indicated by the yellow pin on the right figure.

The downscaled climate model projections were obtained for a central point within the area of the project at latitude -34°04'16" and longitude: 18°47'53", located at 2.2 km from the nearest coastal point. The closest part of the area indicated in red in the figure is at 0.7km for the coast, and the highlighted area is at an elevation of more than 10m with respect to sea level.

3.2 Observed climate variability and recent changes

Climate data

- For all the climate drivers, except for wind speed and solar irradiance, the Copernicus Climate Change Service (C3S) ERA5 reanalysis at 25 km resolution is used as a proxy for observed site conditions. Therefore, the limitations of the ERA5 data set to resolve very localised effects should be taken into account when interpreting the data.
- The wind speed for the baseline period has been obtained from the Vortex global mesoscale layer at 3 km resolution.
- Solar irradiance is obtained from the Global Solar Atlas.
- Water Level data are obtained from satellite data available through the Copernicus Climate Change Service (C3S).

Observed climate

Table 4 shows the results for a series of climate drivers (labelled as hazard metrics) listed on the third column, related to temperature, precipitation, wind, radiation, and extreme precipitation. The definition of the metrics and a description of how they are calculated can be found in Appendix A.

The third and fourth columns indicate the units and the long-term average (reference) over the baseline period (2000-2019). The reference values for extreme wind and precipitation are the extreme values calculated over the baseline period.

The fifth and sixth columns indicate the inter-annual variability and its units (IAV, the standard deviation of the annual mean values) over the baseline period. For instance, the inter-annual variability (IAV) is shown as an absolute value for temperatures and indices such as heat or cold waves, consecutive dry or wet days, and wet bulb globe temperature (WBGT), and as a % of the long-term average (reference) for the other metrics.

The Wet bulb Globe temperature (WBGT) captures the combined effects of air temperature, humidity, wind and radiative forcing on heat transfer between the environment and the human body, being an accepted international standard for the assessment of heat stress. The WBGT chronic index indicates the average value of the WBGT index over the three hottest months of the year. For each location, the three hottest months are chosen as the three consecutive hottest months in the ERA5 climatology over the period 2000 - 2019. As a reference, a WBGT equal to 28°C is the cut-off value for heavy labour being limited to 50% of the time.

The Fire Weather Index (FWI) is a meteorologically based index that estimates potential fire intensity per unit length of fire front based on weather conditions [Van Wagner 1987]. The Fire Weather Index chronic is the average value of the FWI over the days when the fire intensity is larger than 11.2, when fire risk is moderate or higher. This metric does not take into account the fact that the actual fire risk is reduced if combustion material is not available in the site.

Agricultural and hydrological droughts are identified using the Standardised Precipitation Evapotranspiration Index (SPEI) that measures the climatic water balance (precipitation minus evapotranspiration) at different time scales [Vicente-Serrano 2010]. The SPEI index is computed for 3 (SPEI3) and 12 (SPEI12) months for agricultural and hydrological droughts respectively. A month is identified as in drought state when the SPEI value for that month is smaller than a threshold that indicates water stress (see Appendix A for more details).

				Baseline 2000-2019 Observed Climate	
Category	Hazard Metric	Units	Reference	Units	IAV
Ocean Related	**Sea Level Rise**	cm	5.1	cm	2.5
Radiation Related	**Mean Daily DHI**	Wh/m2	1881	%	1.2
Radiation Related	**Mean Daily GHI**	Wh/m2	5238	%	1.2
Temperature Related	**Cold Wave Index**	days/year	13	days/year	9
Temperature Related	**Fire Weather Index Chronic**	-	14.8	-	1.6
Temperature Related	**Heat Wave Index**	days/year	7	days/year	7
Temperature Related	**Icing Days Index**	days/year	0	days/year	0
Temperature Related	**Mean Daily Temperature**	degC	16.2	degC	0.2
Temperature Related	**Max Daily Temperature**	degC	19.8	degC	0.3
Temperature Related	**Min Daily Temperature**	degC	13.2	degC	0.2
Temperature Related	**Wet Bulb Globe Temperature Chronic**	degC	18.4	degC	0.3
Water Related	**Consecutive Dry Days**	days/year	24	days/year	8
Water Related	**Consecutive Wet Days**	days/year	7	days/year	2
Water Related	**Extreme Precipitation**	mm/day	65	%	-
Water Related	**Mean Daily Precipitation**	mm/day	2	%	18
Water Related	**Hydrological Drought Index**	month	18	month	-
Water Related	**Agricultural Drought Index**	month	12	month	-
Wind Related	**Mean Daily Wind Speed @10**	m/s	5.0	%	4.2

Table 4: baseline reference values for a set of representative metrics for the period 2000-2019.

3.3 Future projections

Climate data, scenarios and uncertainty

Projections of changes in future climate are based on climate model simulations. Even though the physical and chemical processes in the climate system follow known scientific laws, the complexity of the system implies that many simplifications and approximations have to be made when modelling the system. The choice of approximations creates a variety of physical climate models [IPCC 2021]. There are different sources of uncertainties in climate model projections. Climate forcing or scenario uncertainty is introduced by the fact that to simulate future climate, the models are run using different scenarios of anthropogenic forcings that represent plausible but inherently unknowable future socio-economic development [Riahi et al. 2017]. Climate model and climate variability uncertainties are due to our incomplete knowledge of the climate system, the limitations of computer models to simulate it, and the system's non-linearity. The relative and absolute importance of these different sources of uncertainty depends on the spatial scale, the lead-time of the projection and the variable of interest [Hawkins et al 2009]. At shorter time scales, in many cases, the current natural variability of the climate system and other non-climatic drivers of risks will have a higher impact than the climatic changes driven by changes in atmospheric concentrations of greenhouse gases.

In this report, projected changes in the climate variables are obtained using the Coupled Model Intercomparison Project 6 (CMIP6) climate models [Eyring et al (2016]. Models' projections are analysed for three Shared socio-economic pathways (SSPs): SSP2-4.5, SSP3-7.0 and SSP5-8.5 [Riahi et al. 2017]. The SSPs describe alternative socio-economic futures. SSP5 represents a fossil-fuelled development pathway, SSP3 is more pessimistic in terms of future economic and social development, and SSP2 is a middle-of-the-road development scenario (see Glossary for more details). SSP2 results in a global warming of between 3.8 and 4.2C, SSP3 in a range of 3.9 to 4.6C, and SSP5 in a range of between 4.7 and 5.1C, in all cases with respect to pre-industrial global mean temperatures.

By taking into account three emissions' scenarios and an ensemble of climate models, climate model formulation and climate forcing uncertainties are encompassed in this analysis.

Projected climate

Projections of the impacts of anthropogenic climate change on the different climate metrics are obtained by statistically downscaling [Cannon 2018] the CMIP6 ensemble of climate models. The downscaling step ensures that biases due to the coarse resolution of climate models (between 100 and 200 km) are corrected using as a proxy for observations the ERA5 reanalysis for most of the variables, and the Global Solar atlas for irradiation. This increases the resolution to 25km2. See Appendix A for more details.

Tables 5 to 7 summarise the main changes for selected climate metrics at the location of the project, for emission scenarios SSP2-4.5, SSP3-7.0 and SSP5-8.5 respectively, and for two projection horizons: short term (2020-2039) and mid term (2040-2059). Assuming a lifetime of between 20 and 30 years, these periods cover the expected lifetime of the project.

For each scenario, the tables show the median of the changes across all climate models (ensemble median) and the likely ranges. The likely range is bounded by the 17th (likely range low) and the 83rd (likely range high) percentiles of the distribution of changes across the models' ensemble, except for sea level rise where it represents the 5%-95% confidence interval.

Changes for temperature metrics, and the heat stress indices are expressed as the difference between the projection and the baseline horizons in degrees Celsius, or days/year respectively. For instance, for the SSP2-4.5 scenario and the short-term horizon, the ensemble median of the projected mean daily temperature will be 0.4°C warmer than the reference value in the baseline period at the location of the project.

Changes for mean daily precipitation, radiation, wind speed, and extreme precipitation, are expressed as the percentage changes between the projection and the baseline horizons.

The column labelled 'confidence' (columns eighth and twelfth in tables 5 to 7) indicate the level of confidence in the sign of the change represented by the ensemble median. The level of confidence is defined as

- High: when more than 80% of the models project changes with the same sign as the ensemble median,
- Medium: when between 60 and 80% of the models project changes with the same sign as the ensemble median,
- Low: otherwise.

For instance, for scenario SSP2-4.5 (Table 5), the level of confidence in the direction of change for the mean daily temperature is High because 100% of the models project positive changes in mean temperature, i.e., the same direction of change as the ensemble median which is +0.4°C in this case.

The confidence level, together with the uncertainty range, can be used to evaluate the robustness of the projected changes, i.e., the higher the confidence level the more robust the projected direction of change in the CMIP6 downscaled ensemble.

				Short Term Horizon 2020-2039 Change				Mid Term Horizon 2040-2059 Change			
Category	Emissions Scenario	Hazard Metric	Change Units	Ensemble Median	Likely Range	Likely Range	Confidence	Ensembl e Median	Likely Range	Likely Rang	Confidenc e
Ocean Related	SSP2-4.5	**Sea Level Rise**	cm	**10.2**	6.1	14.7	-	**22.0**	14.8	30.6	-
Radiation Related	SSP2-4.5	**Mean Daily DHI**	%	**0.1**	-0.1	0.5	Medium	**0.0**	-0.5	0.3	Low
Radiation Related	SSP2-4.5	**Mean Daily GHI**	%	**-0.2**	-0.4	0.1	Medium	**0.3**	-0.1	0.5	Medium
Temperature Related	SSP2-4.5	**Cold Wave Index**	days/year	**-3**	-7	0	High	**-6**	-10	-4	High
Temperature Related	SSP2-4.5	**Fire Weather Index Chronic**	-	**0.5**	0.2	0.9	High	**0.7**	0.1	1.0	High
Temperature Related	SSP2-4.5	**Heat Wave Index**	days/year	**5**	2	7	High	**10**	5	14	High
Temperature Related	SSP2-4.5	**Icing Days Index**	days/year	**0**	0	0	High	**0**	0	0	High
Temperature Related	SSP2-4.5	**Mean Daily Temperature**	degC	**0.4**	0.3	0.5	High	**0.8**	0.6	0.9	High
Temperature Related	SSP2-4.5	**Max Daily Temperature**	degC	**0.4**	0.2	0.6	High	**0.9**	0.6	1.0	High
Temperature Related	SSP2-4.5	**Min Daily Temperature**	degC	**0.4**	0.2	0.5	High	**0.8**	0.6	0.9	High
Temperature Related	SSP2-4.5	**Wet Bulb Globe Temperature Chronic**	degC	**0.4**	0.2	0.6	High	**0.8**	0.6	0.9	High
Water Related	SSP2-4.5	**Consecutive Dry Days**	days/year	**0**	-1	2	Medium	**-1**	-2	3	Low
Water Related	SSP2-4.5	**Consecutive Wet Days**	days/year	**0**	-1	0	Medium	**0**	-1	0	Medium
Water Related	SSP2-4.5	**Extreme Precipitation**	%	**32.4**	4.4	89.0	High	**30.9**	7.7	85.1	High
Water Related	SSP2-4.5	**Mean Daily Precipitation**	%	**-2**	-7	5	Low	**-6**	-10	-2	High
Water Related	SSP2-4.5	**Hydrological Drought Index**	month	**12**	-9	35	Medium	**23**	2	62	High
Water Related	SSP2-4.5	**Agricultural Drought Index**	month	**8**	2	12	High	**16**	10	23	High
Wind Related	SSP2-4.5	**Mean Daily Wind Speed @10**	%	**-0.2**	-1.3	0.7	Low	**-0.3**	-1.2	1.0	Low

Table 5: Projected changes for selected climate metrics for the SSP2-4.5 scenario.

				Short Term Horizon 2020-2039 Change				Mid Term Horizon 2040-2059 Change			
Category	Emissions Scenario	Hazard Metric	Change Units	Ensemble Median	Likely Range	Likely Range	Confidence	Ensemble Median	Likely Range	Likely Rang	Confidence
Ocean Related	SSP3-7.0	**Sea Level Rise**	cm	**10.0**	6.3	14.3	-	**23.2**	16.1	31.8	-
Radiation Related	SSP3-7.0	**Mean Daily DHI**	%	**0.2**	-0.1	0.6	Medium	**0.1**	-0.3	0.8	Low
Radiation Related	SSP3-7.0	**Mean Daily GHI**	%	**-0.2**	-0.7	0.1	Medium	**-0.1**	-0.7	0.4	Low
Temperature Related	SSP3-7.0	**Cold Wave Index**	days/year	**-5**	-6	-1	High	**-8**	-11	-7	High
Temperature Related	SSP3-7.0	**Fire Weather Index Chronic**	-	**0.2**	-0.2	1.0	Medium	**0.7**	-0.1	1.2	Medium
Temperature Related	SSP3-7.0	**Heat Wave Index**	days/year	**3**	1	7	High	**12**	8	19	High
Temperature Related	SSP3-7.0	**Icing Days Index**	days/year	**0**	0	0	High	**0**	0	0	High
Temperature Related	SSP3-7.0	**Mean Daily Temperature**	degC	**0.5**	0.3	0.5	High	**0.9**	0.8	1.1	High
Temperature Related	SSP3-7.0	**Max Daily Temperature**	degC	**0.4**	0.3	0.6	High	**1.0**	0.8	1.2	High
Temperature Related	SSP3-7.0	**Min Daily Temperature**	degC	**0.5**	0.3	0.5	High	**0.9**	0.8	1.1	High
Temperature Related	SSP3-7.0	**Warm Days Index**	days/year	**8**	3	11	High	**21**	16	27	High
Temperature Related	SSP3-7.0	**Wet Bulb Globe Temperature Chronic**	degC	**0.4**	0.3	0.5	High	**0.9**	0.7	1.1	High
Water Related	SSP3-7.0	**Consecutive Dry Days**	days/year	**1**	-3	5	Low	**0**	-2	4	Low
Water Related	SSP3-7.0	**Consecutive Wet Days**	days/year	**0**	-1	1	Low	**0**	-1	0	Low
Water Related	SSP3-7.0	**Extreme Precipitation**	%	**31.6**	10.0	70.5	High	**18.1**	4.6	71.1	High
Water Related	SSP3-7.0	**Mean Daily Precipitation**	%	**2**	-4	4	Medium	**-5**	-9	0	High
Water Related	SSP3-7.0	**Hydrological Drought Index**	month	**2**	-9	13	Low	**18**	5	45	High
Water Related	SSP3-7.0	**Agricultural Drought Index**	month	**0**	-3	10	Medium	**10**	3	23	High
Wind Related	SSP3-7.0	**Mean Daily Wind Speed @10**	%	**0.6**	-0.3	2.0	Medium	**0.9**	0.0	1.6	Medium

Table 6: Projected changes for selected climate metrics for the SSP3-7.0 scenario.

				Short Term Horizon 2020-2039 Change				Mid Term Horizon 2040-2059 Change			
Category	Emissions Scenario	Hazard Metric	Change Units	Ensemble Median	Likely Range	Likely Range	Confidence	Ensemble Median	Likely Range	Likely Rang	Confidence
Ocean Related	SSP5-8.5	**Sea Level Rise**	cm	**10.6**	6.6	15.0	-	**24.8**	17.4	33.8	-
Radiation Related	SSP5-8.5	**Mean Daily DHI**	%	**0.0**	-0.6	0.3	Low	**0.0**	-0.6	0.7	Low
Radiation Related	SSP5-8.5	**Mean Daily GHI**	%	**0.1**	-0.2	0.6	Medium	**0.3**	-0.4	0.6	Medium
Temperature Related	SSP5-8.5	**Cold Wave Index**	days/year	**-4**	-6	-2	High	**-9**	-10	-7	High
Temperature Related	SSP5-8.5	**Fire Weather Index Chronic**	-	**0.4**	0.0	0.8	High	**1.1**	0.6	1.5	High
Temperature Related	SSP5-8.5	**Heat Wave Index**	days/year	**5**	1	9	High	**14**	10	22	High
Temperature Related	SSP5-8.5	**Icing Days Index**	days/year	**0**	0	0	High	**0**	0	0	High
Temperature Related	SSP5-8.5	**Mean Daily Temperature**	degC	**0.4**	0.3	0.6	High	**1.0**	0.9	1.2	High
Temperature Related	SSP5-8.5	**Max Daily Temperature**	degC	**0.5**	0.3	0.6	High	**1.0**	0.9	1.3	High
Temperature Related	SSP5-8.5	**Min Daily Temperature**	degC	**0.4**	0.3	0.5	High	**1.0**	0.9	1.2	High
Temperature Related	SSP5-8.5	**Warm Days Index**	days/year	**10**	6	11	High	**23**	18	29	High
Temperature Related	SSP5-8.5	**Wet Bulb Globe Temperature Chronic**	degC	**0.3**	0.2	0.6	High	**1.0**	0.8	1.2	High
Water Related	SSP5-8.5	**Consecutive Dry Days**	days/year	**0**	-3	3	Low	**2**	-2	4	Medium
Water Related	SSP5-8.5	**Consecutive Wet Days**	days/year	**0**	-1	0	Medium	**0**	-1	0	Medium
Water Related	SSP5-8.5	**Extreme Precipitation**	%	**43.0**	14.7	82.2	High	**23.4**	3.8	54.9	High
Water Related	SSP5-8.5	**Mean Daily Precipitation**	%	**-2**	-8	1	Medium	**-7**	-11	-3	High
Water Related	SSP5-8.5	**Hydrological Drought Index**	month	**15**	-3	30	Medium	**37**	9	70	High
Water Related	SSP5-8.5	**Agricultural Drought Index**	month	**7**	2	15	High	**18**	5	25	High
Wind Related	SSP5-8.5	**Mean Daily Wind Speed @10**	%	**0.3**	-0.4	1.1	Medium	**0.7**	-0.6	1.2	Medium

Table 7: Projected changes for selected climate metrics for the SSP5-8.5 scenario.

The following tables include a brief summary of the expected changes based on the scenario analysis results for temperature, water, coastal and ocean, wind and radiation related climate variables.

Temperature Related
Temperature related metrics show robust positive changes in the case of **mean, max and min daily temperatures, heat waves** and **chronic WBGT** (high confidence in the projected changes in all cases for all scenarios). In general, the projected changes are similar between SSPs in the short term horizon, but become more different in the medium term, being largest for SSP5-8.5 and smallest for SSP2-4.5, consistently with the former scenario corresponding to larger and the latter to the smaller

global warming respectively. In addition, the uncertainty ranges show that at least 83% of the models project increases in temperature related metrics for all SSPs and projection periods. Minimum temperatures are projected to increase and consequently metrics related to cold events, such as cold wave days decrease for all scenarios and projection periods.
Changes in chronic **fire weather** are small in all cases, less than 2 units in absolute value including the uncertainty ranges. Since the baseline value is 14.8 (Table 4), the meteorological conditions that favour the occurrence of wildfires are projected to remain within the medium intensity range for FWI severity in this site.

Water Related

Mean daily **precipitation** is projected to decrease by a small amount (ensemble median around 2%) in the short term, albeit with a large uncertainty (low confidence in the sign of change). In the mean term however, projected changes are consistently negative (between 5 and 7% depending on the scenario), and with high confidence in projected decreases.
The ensemble medians of the projected changes in **extreme precipitation** are positive for the three scenarios and both projection periods. The uncertainty ranges are large but there is high confidence in increases in extreme precipitation in this site. When analysing these results however, it must be taken into account that the extreme value fitting over a 20-year period is very sensitive to the existence of outliers over that period; that presumably explains in part the large uncertainty ranges in the extreme precipitation values.
Hydrological and **agricultural droughts** as quantified by the SPEI12 and SPEI3 indices are projected to increase for all scenarios. Similar to the signal observed for the decrease in precipitation, the increase in the number of drought months show a robust positive signal in the medium term (high confidence in the projections).

Coastal and Ocean

Sea level is projected to increase for all scenarios, by about 10cm (ensemble median) with respect to the 1995-2014 average in the short term, and more than 20cm in the medium term, with larger increases for the higher emissions scenarios (SSP5-8.5).
These values do not include the effects of tides and storm surges, therefore representing only smooth (chronic) changes in sea level.
Probabilistic projections of **extreme total water levels** (ETWL) including changes in mean sea level, tides, waves and storm surges are obtained by superimposing the historical distribution of ETWL with the projected sea level rise. Table 8 shows the projected values for the nearest point to the location of the site in the database, and for the short (2030s) and mid (2050s) projection period , for the three emissions scenarios.

	BASELINE 2000-2018	SHORT TERM- 2030S			MID TERM- 2050S		
		Median	5%	95%	median	5%	95%
SSP2-4.5	1.88	2.16	2.00	2.39	2.28	2.09	2.56
SSP3-7.0	1.88	2.16	2.01	2.39	2.30	2.10	2.59

SSP5-8.5	1.88	2.16	2.01	2.41	2.31	2.11	2.58

Table 8: Historical and projected 100 return period ETWL in meters. The values in the table correspond to the nearest point to the location of the site in the data set. For each scenario and time period the values represent the median and 5 and 95% percentiles of the probability distribution of the projected values. ETWL is a measure with respect to the mean sea level for the period 1995-2014.

Wind Related

The ensemble medians of changes in 20-year averages of **mean daily wind speed** at 10m show very small decreases for SSP2-4.5 with no robust signal (low confidence in the changes), and small increase for the other two scenarios with medium confidence in the direction of change. The projected changes, including the uncertainty ranges are smaller than the IAV at the site (4.2%).

Solar Related

Projected changes in **mean Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI)** are very small, less than 1% including the uncertainty range.

4.Physical climate risks and opportunities

Due to the lack of detailed information about the different components of the Project, in this section, the physical risks identified refer only to the hazard component of the risk. Unless otherwise stated, vulnerability and exposure of the assets are not taken into account when assigning the risk levels. For instance, wildfire risk considers only the meteorological conditions favouring the occurrence of wildfires, without taking into account other factors such as the characteristics of the surrounding environment (is there vegetation that can serve as fuel?), or the existence of protective measures already in place.

Focusing therefore on the hazard component, and based on the climate drivers of impacts on PV solar and energy infrastructure (section 2), and their projected changes under climate change (section 3), the corresponding physical risks and opportunities are estimated in this section by assigning different risk levels to changes in frequency and intensity for extreme events (acute risks), or to long term averages for secular changes (chronic risks).

4.1 Methodology

Climate change can impact the energy infrastructure through acute or extreme events, and through secular or chronic changes. In the case of acute changes, the intensity and magnitude, frequency, duration, timing and spatial extension of a region's extreme events could be altered. In this report the risk associated with extreme events takes into account two of these dimensions, intensity and frequency.

Chronic changes correspond to variables that change monotonically, such as for instance continuous increases of mean air temperature or mean sea level. In this case the level of risk is linked to percentage changes of the metric with respect to the chosen baseline period.

The damaging thresholds that determine the risk levels for chronic and acute risks are summarised in Appendix B.

To identify the overall risk that would be relevant for any type of infrastructure the following categories of acute and chronic risks are included:

- **Extreme Heat stress (human):** as indicated by the Wet Bulb Globe Temperature (WBGT) which is an indicator of heat stress on humans
- **Extreme Fire Conditions:** as indicated by the Fire Weather Index (FWI) which is an indicator of meteorological conditions that favour the occurrence of wildfires
- **Extreme Precipitation (Flooding)**: using, as a proxy for pluvial and surface flooding, the extreme precipitation index. We note here that flooding is strongly dependent on other factors, beyond the meteorological conditions, more information than that provided by climate models should be used to compute the overall risk of flooding

- **Water scarcity (Hydrological and Agriculture):** as indicated by changes in the number of months in drought conditions for hydrological and agricultural droughts. Note that to estimate water stress, information about water demand is also required.
- **Hail**: as indicated by the Average annual probability (in days/year) of hail with a diameter >2.5 cm, normalised to areas of 100 km x100 km. This is available only for the historical period.
- **Extreme wind (storminess)**: extreme wind speeds at 10m height are used to identify damaging meteorological conditions. These would be mainly due to midlatitude storms since the project area is not affected by Tropical Cyclones.
- **Coastal inundation**: as indicated by the 1 in 100 years return period Extreme Total Water Level that includes the effects of sea level rise and storm surge.
- **Coastal erosion**: as indicated by shoreline changes that take into account sea level rise and future changes in meteorological drivers (Vousdoukas, 2020).

Coastal erosion and coastal inundation are included in this report due to the proximity of the project area to the coast.

Soil related risks (only available for the historical period) include (see Appendix B for more details)

- **Subsidence:** calculated as a combination of the susceptibility of a location to experience subsidence and the probability of groundwater depletion .
- **Landslide:** based on the estimated annual frequency of significant landslides per square kilometre.
- **Erosion** (Croplands): as indicated by the soil displacement by water erosion.

Specific risks associated with acute and chronic hazards relevant for solar PV technologies are also considered, including extreme wind as an acute hazard, and secular changes in mean Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI), mean temperature, wind at 10m height, and number of hot and cold days.

Risk levels and climate modelling uncertainty

The projection of changes in climate drivers of impacts obtained using the ensemble of Climate Scale downscaled climate model projections (Section 3 and Appendix A) are used to estimate the physical risks. Given the historical values or projected changes of a climate metric, for each model simulation, projection period and emissions' scenario, the risk is computed using the approach described in Appendix B. Risk categories include very low, low, medium and high. Due to the uncertainty in climate model projections, in some cases different models project different risk categories for the same scenario and projection period. To take into account this uncertainty, an overall **risk level** and a **level of confidence** in the projections is assigned using the criteria described in Table 9. The selection of thresholds in the third column is based on expert judgement, informed by the criterion used by the IPCC AR6 report (IPCC 2021) to define robust changes.

Confidence Levels		Definition
HC	High Confidence	when >80% models fall in the same category
MC	Medium Confidence	when between 60% and 80% of the models fall in the same category or more than 60% of the models fall across two contiguous categories
LC	Low Confidence	when none of the above is satisfied
	Risk Levels	**Maximum level of confidence achievable**
	High	HC
	Medium-High	MC
	Medium	HC
	Low-Medium	MC
	Low	HC
	Very Low-Low	MC
	Very Low	HC

Table 9: Risk levels and definition of confidence levels

In this way, the risk category can be used to identify assets that are, or might be threatened in the future by different hazards, and the level of confidence offers an indication of how robust this projection is according to the climate models considered in the analysis. Note that, by definition, there can be at most medium confidence when the risk level falls across two categories (e.g, medium-high).

4.2 Climate change related risks

The acute and chronic risks identified for general infrastructure and solar technology are discussed in this section.

4.2.1 General infrastructure risks

In this section we discuss the risks that can affect any type of infrastructure, including energy infrastructure.
The project layout provided indicates that, in addition to solar PV components, there will be transmission and distribution cables and a substation. No specific risks other than those affecting general energy infrastructure have been identified for this type of equipment.

Acute risks

Table 10 summarises the acute risk metrics and the identified risk levels. The first and third columns indicate the risk metrics and risk level projected respectively, while the second column indicates the potential impact. The last column references supplementary information/data that, in addition to Climate Scale data, was used to identify the risks. The damaging thresholds that determine the risk levels are summarised in Appendix B.
In cases where risks are already identified in the baseline period, it is likely that adaptation measures to reduce the vulnerability of the sites can be put in place in the planning stage of the project.

Metric	Potential impact	Risks identified 2020-2039, 2040-2059	Comments
Extreme Heat stress (human)	Heat stress that can affect the workforce.	**Very Low-Low risk** from the baseline period onwards for all scenarios (High confidence).	
Extreme Fire conditions	Damage to infrastructure due to wildfires.	**High risk** from the baseline period onwards and all scenarios (High confidence).	This metric does not take into account the fact that the actual fire risk is reduced if combustion material is not available in the site.
Extreme precipitation (Flooding)	Pluvial and surface flooding as a result of extreme precipitation.	**Low** risk from the baseline period onwards and all scenarios (High confidence).	Extreme precipitation is used as a proxy for pluvial and surface flooding. Even though extreme precipitation is projected to increase in this location, the projected intensities remain within the range of intensities corresponding to Low risk (see Appendix B).
Coastal inundation	Damage to coastal infrastructure due to sea level rise and storm surge.	**Low risk**, based on data from Climate Scale modelling study and information about the project.	The 1 in 100-year return period Extreme Total Water Level is used as an indicator to identify coastal inundation risks. The infrastructure is planned to be located at more than 0.7km from the coast and more than 10m above sea level. Projected increases by 2050s in ETWL are no larger than 70 cm (considering uncertainty ranges and the three emissions' scenarios - see table 8) than the historical ETWL.
Landslides	Damage to infrastructure	**Very Low** (only historical period available)	Source: World Bank Global Landslide Hazard Map

Table 10 Projected acute risks for general infrastructure assets. See Appendix B for detailed definitions of risk levels.

Note that hail and extreme wind risks are discussed in the **Solar PV** risks section below.

Chronic risks

Table 11 summarises the chronic risk metric considered and the identified risk levels for all SSPs scenarios, and for the periods 2020-2039 and 2040-2059, unless otherwise stated.

The first and third columns indicate the risk metrics and risk level projected respectively, while the second column indicates the potential impact. The last column references supplementary information/data that, in addition to Climate Scale data, was used to identify the risks. The damaging thresholds that determine the risk levels are summarised in Appendix B.

Metric	Potential impact	Risks identified 2020-2039, 2040-2059	Comments
Water scarcity (hydrological and agriculture)	Reduce water availability for different uses: domestic, industrial, agricultural, etc.	**Medium risk** of **agricultural droughts** in the baseline period, increasing to High (SSP2-4.5 and SSP5-8.5) or Medium-High (SSP3-7.0) in the mid term (2040-2059) (Medium Confidence). **High or Medium-High risk** of **hydrological droughts** from the baseline onwards and all scenarios (High Confidence)	See **Solar PV** risks section below for impacts on PV solar technology.
Coastal erosion	Damage to coastal infrastructure.	**Low risk**, based on data from one modelling study (limited evidence-low confidence) and information about the project. RCP4.5 and RCP8.5 in 2050 with respect to 2010.	The ensemble median of the projected changes is -48m (with 90% range: -90m to -20m) for RCP4.5, and -50m (with 90% range: -110m to -10m) for RCP8.5. This data corresponds to the point along the coast in the database that is closest to the location of the project. Because the area of the project is at least at about 700 metres from the coast, the reported values for shore retreat represent a low risk to the project. Source: Vousdoukas, 2020.
Soil erosion	Damage to infrastructure.	**Low** (only historical period available)	Source: Borrelli et al.,2022.

SUBSIDENCE	Damage to infrastructure	**High** (only historical period available)	Potential subsidence is calculated as a combination of the susceptibility of a location to experience subsidence and the probability of groundwater depletion. Source: Herrera Garcia et al (2021)

Table 11: Projected chronic risks for general infrastructure assets.

Note that solid related hazards (soil erosion, landslides and subsidence) were derived from global data sets. A localised geotechnical study would be necessary to confirm the findings.

4.2.2 Solar PV

Acute risks

Table 12 summarises the risk metrics and the identified risk levels for acute risks for solar PV.The second column in the table indicates the area of impacts.

Metric	Potential impact	Risks identified for periods: 2020-2039 2040-2059	Comments
Extreme wind (storminess)	Damage to infrastructure due to extreme winds.	**Low risk** with Medium confidence in the short and medium projection periods.	Extreme wind speeds are not projected to change significantly in this location (ensemble median of changes between -1.4% and 4.6% depending on scenario and projection period), with a large model spread (Low or Medium confidence in the direction of change). In all cases the projected intensities remain within the range of intensities corresponding to Low risk (see Appendix B).
Hail	Damage to PV panels surface	**Very Low**	Based on a modelling study by Prein et al (2018), the annual hail probability in a 100x100km area, in the region where the project is located, is very low, less than 0.15 days/year (Prein at al, 2018). This is based on a study of environmental conditions that favour the formation of hail storms, since observational data is

			not available for this region. Due to lack of observations and process understanding, and limited number of studies, current and future climate change impacts on hailstorms is highly uncertain (Raupach et al (2021)).

Table 12: Acute physical risks for Solar PV

Dust and dust storms also represent a risk for solar PV production since an increase in dust deposition could decrease power output and increase the need of water for cleaning.The current generation of climate models, however, cannot simulate dust and sand storms. Therefore, there is no information about the potential impacts of climate change on this phenomenon.

Given that the project area is located in a region where droughts are projected to increase (under all emissions' scenarios), and that soiling could reduce PV efficiency, the techniques implemented for panel cleaning should take into account that water scarcity could severely limit the availability of water for this use.

Chronic risks

Table 13 summarises the risk metrics and the identified risk levels for chronic risks for solar PV.The second column in the table indicates the area of impacts.

Chronic Metric	Potential impact	Risks identified for periods: 2020-2039 2040-2059
Mean irradiation (global horizontal irradiance, and diffuse horizontal irradiance) reduction	Energy / Revenue Loss in revenue due to change in irradiation.	**Very Low** or **Low risk** (reductions in irradiance less than 2%) for all scenarios (Medium confidence).
Mean Air Temperature - increase	Energy / Revenue Loss in revenue due to chronic increases in temperature.	**Low ris**k (increases less than 2C) with High Confidence for 2020-2039. For SSP3-7.0 and SSP5-8.5 the risk is **Low-Medium** for 2040-2059 with Medium confidence.
Mean wind speed@10m - reduction	Energy / Efficiency Loss of revenue due to decrease in wind speed	**Very Low or Low Risk** (reductions smaller than 1%) with Medium confidence.
Days in heat wave condition- increase	Energy / Revenue Loss in revenue due to chronic increases in days in extreme temperature conditions.	**Very Low Risk** (less than 100 days/year overcome the P90 baseline temperature) with High confidence.

Table 13 Climate drivers of impacts on solar PV (first column), area of impacts (second column) and identified risks (third column). See Appendix B for detailed definition of risk levels.

As indicated in Table 12, risks associated with reduction in GHI and DHI are very low. For both, models show small increases or decreases depending on the scenario and period, but always smaller than 1% in magnitude.

5. Decommissioning and disposal impacts

5.1 Setting the scene

Decommissioning and disposal of power plants occurs at the end of the useful life of a project. PV plants usually have a lifespan that covers from 20 to 30 years from their installation. At the time of decommissioning, they will have to comply with the legislation in place which normally will follow several industry best practice guidelines as well as specific local regulations (which may or may not be in place right now, as legislation develops over time and 3 decades is a long period of time).

This section of the report will cover current best practices and assume sensible guidelines for the decommissioning of the plant.

5.2 Local framework

South Africa already has some policy regarding decommissioning strategies. For example, the Radioactive Waste Management Policy and Strategy (RWMPS) issued by the former DoE (Department of Energy) for South Africa in 2005 states that to minimize the burden on future generations, decommissioning and closure of facilities should be implemented as soon as practicable. The policy defines the principles that should be considered in developing the strategy on radioactive waste management. It should be noted that there are still some provisions of the policy that need to be enacted or approved by the Government, as a national decommissioning policy and strategy needs to be developed. The Minister of DMRE (Department of Mineral Resources and Energy) is responsible for developing and implementing national policy, preparing, and initiating legislation and performing any other executive function provided for in the Constitution or in national legislation (sec 85(2)(b), (d) and (e) of the Constitution).

Although the PV plant will obviously not produce any radioactive waste, it is to be expected that similar policies will be applicable to electrical waste and the decommissioning of PV plants over the next few years.

5.3 Decommissioning tasks

For PV plants, the decommissioning phase contemplates the removal of facility components. The associated tasks and costs relate to the construction (at the time of the decommissioning) because the same steps are performed but in reverse order. The project may be decommissioned when the owner/operator decides to retire the Solar Facility or other contractual commitments, such as with the landowner or environmental that require them to do so.

Normally the following items need to be considered when decommissioning a PV plant:

Decommissioning items.

Item	Description
Contractor fees	
Mobilization/Demobilization	Several large-scale machinery such as graders, bulldozers, excavators, utility trucks, etc. will be brought back to the site utilizing the existing roads.
Supervisory/Management	The supervision will be carried out during the whole decommissioning process. The price for this task depends on the PV plant design and size.
Permitting fees	Permits depend on local authorities and generally managed by the plant owner
PV Collection System	
Removal of panels	The modules are disconnected and removed from the mounting structures. Disassembly costs for the solar modules are based on assumptions but generally in line with assembly costs.
Haul of panels into pallets[3]	Once the solar modules are removed, they will be packaged per manufacturer or approved recycler's specifications and transported to a predetermined location for resale, recycling, or disposal. If the modules are not reused, glass, silicon and aluminium frames will be recycled.
Racking removal	
Remove steel posts	All racking posts driven into the ground will be disassembled, pulled, and removed using standard tools.
Remove racking tables	The vertical posts will be removed using heavy equipment.
Removal foundations	Racking components will be disassembled and removed from the steel foundation posts and shipped to a metal recycling facility and thus the cost of decommissioning will be reduced.
Electrical equipment	
AC/DC wire removal	The electrical wiring installed underground and fixed to the mounting structures are removed. To remove the underground wires, the original trenches they are buried in are dug. The wire that is fixed to the mounting structure with a plastic clip is removed manually. The cost is determined by the length of the cables and thus the working time of technicians and heavy equipment on site.
String boxes removal	String boxes are transported off-site to be recycled, in accordance with current standards and best practices. Metal components such as fans and fixtures are disposed of or recycled, when possible.

[3] The scope includes the loading and unloading at the storage area, with the removal of recovered elements for subsequent transport to an authorized recycling facility.

Item	Description
Transformer stations removal	Transformer stations are transported off-site to recycle, in accordance with current standards and best practices. Oil from the transformer is removed on-site to reduce the risk of leakage and then transported to an approved site for disposal.
Interconnection line removal	As the exact interconnection arrangement has not been specified, the uncertainty in this task is higher since it depends on the line support, support's height, structure removal and type of cabling.
Interconnection pole removal	Poles that are not owned by the utility or distribution company are generally removed,
Remove equipment pads	The material is removed from the project location, the aggregate can be processed for salvaging or may be reused as fill for construction.
Site restoration	
Removal of security fence	Fence is removed and broken down into manageable units and recycled at a metal recycling facility (at times, landowners may require keeping the fence intact).
Site cleaning	The affected areas are inspected, thoroughly cleaned, and restored to its pre-construction state.
Grading	The excavation caused by the dismantling of equipment foundations, mounting structures and underground cables is backfilled and levelled.
Seeding and mulching	Disturbed areas are reseeded to promote re-vegetation of the area and to prevent soil erosion.
Salvage/ Recycling	
Recycling / Salvage	Waste generated will be disposed of in accordance with applicable standards at an appropriate facility in accordance with all local and state rules.

5.4 Risks and liabilities

Risks that could be associated with the decommissioning of a PV plant are:

- Personal Safety: During the decommissioning process, there is a risk of accidents or injuries to the workers involved. Handling heavy equipment, working at heights, exposure to chemicals or electricity, among others. Appropriate safety measures must be implemented and compliance with occupational safety standards.
- Environmental Impact: The decommissioning of a photovoltaic park will generate waste and residues that require proper management and disposal. It will be important to follow environmental regulations at the time of decommissioning, as well as to have an adequate waste management plan to prevent soil, water, or air contamination during the process.
- Contamination and Chemical Risks: Some components of photovoltaic panels, such as glass, aluminium, and semiconductor materials, may contain potentially hazardous chemicals. During the decommissioning process, there will be a risk of exposure to these substances if not handled

properly. It is essential to follow safety guidelines and comply with applicable regulations to minimize chemical risks and protect the health of workers and the environment, as well as industry best practices.

5.5 Potential environmental impacts

The decommissioning of a PV plant can have environmental effects:

- Waste Generation: waste is generated and must be professionally managed. This includes solar panels, support structures, cables, and other components. If these wastes are not managed correctly, they can cause soil, water, or air contamination.
- Contaminants in Solar Panels: Depending on the technology, solar panels contain potentially hazardous chemicals, such as cadmium or lead (this applies mostly to thin film modules, most modules are poly or mono crystalline silicon). If not properly handled during decommissioning, these contaminants can be released and cause negative impacts on the environment.
- Impact on Biodiversity: This could include the disturbance of natural habitats, destruction of vegetation, or disruption of wildlife migration routes.
- Greenhouse Gas Emissions: emissions can be generated due to material transportation, machinery use, and waste management. These emissions contribute to climate change and should be controlled and minimized.
- Disturbances such as erosion, sedimentation, or fuel spills near adjacent watercourses or natural features.
- Traffic: Road traffic may temporarily increase due to the movement of decommissioning crews and equipment
- Dust and noise: temporary elevated noise levels from heavy machinery and an increase in particulate matter (dust) in adjacent areas.

Remediation costs

Some of the activities that may be considered to meet industry standards and best practices, include:

- Waste management and disposal: Remediation costs are primarily associated with the proper handling and disposal of waste generated during the decommissioning process. This may include hiring specialized waste management services and safely transporting materials to treatment or recycling facilities.
- Site restoration: After removing the solar panels and structures, site restoration may be required to return it to its original state or for other subsequent uses. This may involve levelling work, vegetation planting, restoration of vegetation cover, or other necessary measures to recover the affected area.

- Monitoring and follow-up: post-decommissioning monitoring and follow-up may be necessary to ensure that there are no residual environmental impacts. This may include soil, water, or air quality analysis, as well as periodic inspections to ensure that no hidden contamination has occurred.

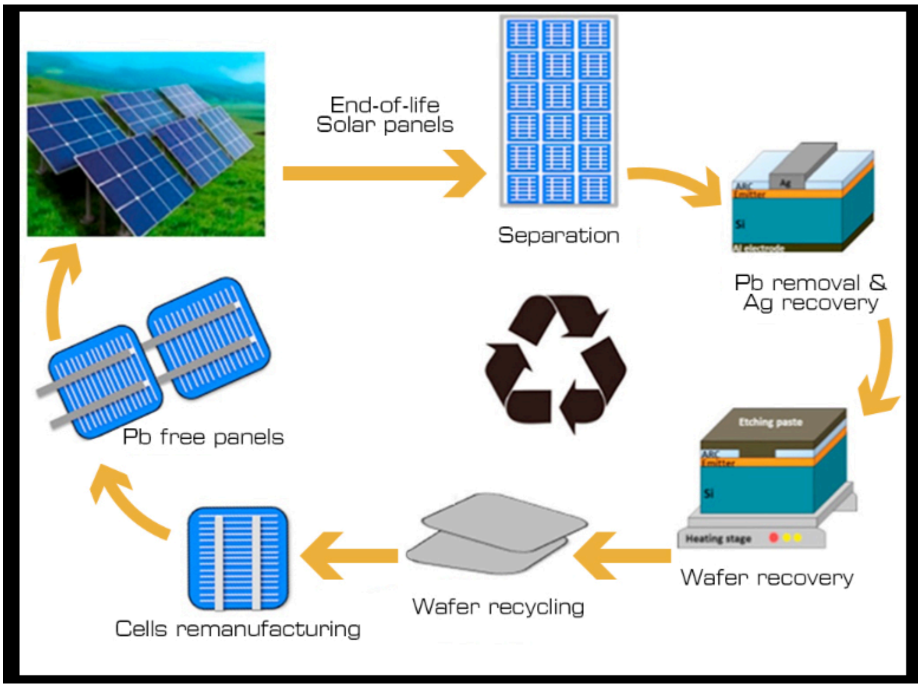
5.6 Recycling

PV plants have several components that can be recycled. Regulation together with recycling technologies are an essential part of achieving a high percentage of recycled components. For instance, the EU Waste Electrical and Electronic Equipment (WEEE) Directive revised in 2012 (2012/19/EU) addresses the waste management of all electronics, including PV modules within the EU. It requires 75%/65% (recovery/recycling rate) of waste PV modules by mass to be recycled through 2016, then increases to 80%/75% through 2018 and to 85%/80% after that date. Reuse, repair, remanufacturing, and repurposing are expected to play key roles in the future to develop a circular economy model based on PV waste manufacturing.

PV modules

End of life (EOL) management could become a significant component of the PV value chain. Recycling PV panels could unlock a stock of raw materials. Available recycling facilities that treat PV modules can meet current WEEE requirements; additional research and development (R&D) is required to meet subsequent WEEE requirements at reasonable cost. There are already companies[4] making use of these targets and can recover up to 95 to 100% of the materials with the most problematic components to recycling being the backsheets and encapsulant materials of the modules.

[4] https://www.pv-magazine.com/2022/10/24/new-industrial-plant-concept-for-end-of-life-pv-panel-recycling/
https://sasil-life.com/wp-content/uploads/2018/05/Sasil-Srl-Slides-Amsterdam-23sett2014.pdf
https://www.pv-magazine.com/2020/05/13/pv-module-recyclers-aiming-for-high-purity-material-recovery/



There are three stages of PV recycling, although the exact process depends on the module technology:

- Delamination
- Material separation
- Material extraction and purification.

For crystalline silicon panels: Solar panels are recycled by chemical, thermal and mechanical processes. The process starts with the removal of the junction box, wires, and frame. Then, the module is shredded, sorted, and separated. The separation of the materials allows them to be subjected to specific recycling processes associated with each material.

CdTe (Cadmium Telluride) solar cells are second-generation solar cells that require a different process. There are several options, for example, shredding of pieces into larger and then into smaller fragments. Then the semiconductor metals are slowly removed. Sodium hydroxide is used to precipitate the metal compounds, and the glass is separated so that it can be reused again.

Another method includes physical fragmentation of small modules. After that, these small pieces are exposed to an atmosphere containing oxygen at 300°C. These conditions result in the delamination of the ethylene vinyl acetate (EVA). Subsequently, these fragments are taken to a 400°C atmosphere containing chlorine gas which causes an etching process. This step of the process generates $CdCl_2$(Cadmium Chloride) and $TeCl_4$ (Tellurium Tetrachloride) that are condensed and precipitated afterwards.

There are other methods that are still being researched and developed.

A second life for the materials depends on the impurity levels achieved. This is an important factor in the recycling process. If these materials can be recovered without the impurities, they have a higher value in the market.

For additional information on the environmental impacts of recycling PV modules, this paper from Thomas et all (2020) offers more detailed insights.

Inverters

The solar inverter recycling process is like that of traditional e-waste – removing hazardous materials, separating valuable materials, scraping reusable material. The most easily recyclable materials are Metals and Printed circuit board assemblies (PCBA). Metals make up 60% of the inverter weight and 90% of metals can be recycled. PCBA make up 40% of the inverter weight and 65% of PCBA can be recycled.

Material/ Component	Weight Percentage	Recyclable Percentage
Plastic	0.44	60%
Metal	59.39	90%
PCBA	38.93	65%
Cable	1.05	65%
Rubber	0.19	0%

Source, Huawei 2020

In Australia, for example, inverters can be taken to the e-waste recycling system where the components are separated, and valuable materials are extracted.

5.7 Risk quantification and conclusions

PV plants are no longer an emerging technology and the impacts of decommissioning of its components are well documented.

Disposing and recycling of the components of the plants is an area that is still developing and although successful policies have been implemented in more mature markets, South Africa will also need to implement suitable regulation to ensure recycling facilities are available locally. If this implementation is successful in the next 20 to 30 years, the risks of sending the components to landfill or environmental liability will be small and manageable. If this is not the case, it is recommended that a budget is set apart to ensure a successful decommissioning phase including recycling of the plant's components, as is currently done in other markets such as the EU or Australia.

6. Summary and recommendations

Building in climate resilience into planned and developing infrastructure is key to avoid increasing risks and losing opportunities[5]. This requires in particular that infrastructure investments make full allowance for the physical risks of climate change (GCF,2023b). It is estimated that the net benefit of investing in more resilient infrastructure across all sectors in low- and middle-income countries would be USD 4.2 trillion, with $4 in benefits for every $1 invested (Hallegatte et al., 2019).

Resilience in renewable energy projects requires an understanding of the implications for CAPEX and OPEX. Developing infrastructure resilient to hazards avoids losses and damages, ensuring consistent yields and reduced maintenance and damage repair costs. However, there are CAPEX implications to designing for harsher climates (GCF, 2023a). These costs need to be weighed against the benefits of a more robust system with lower outyear costs for maintenance, administrative burdens, repair, and downtime/loss of production. We note, however, that the consideration of the implications for CAPEX and OPEX of proposed measures is beyond the scope of this report.

Recommendations for mitigation measures to address the high risk of wildfires and water scarcity are discussed. In the case of hazards where high risks are not identified, the recommendations provided are aimed at building in climate resilience. This is particularly important in cases where the confidence in the projected risks is not high, since this indicates that at present, there is not a robust climate change signal across climate models. Continuous monitoring of the environmental conditions in the future, and the analysis of new climate information as it becomes available are recommended. This new information can be used to compare conditions and performance throughout the life of the project, and revise and adjust mitigation measures if necessary.

The following table summarises the physical risks posed by climate change on general energy infrastructure and PV solar, together with proposed high-level adaptation measures where relevant. In cases where risks are already identified in the baseline period, it is likely that adaptation measures to reduce the vulnerability of the site can be built-in in the development phase of the project.

[5] Resilient infrastructure is infrastructure designed to withstand multi-hazards of appropriate magnitude, taking into account that the design today will need to withstand for example, more extreme pluvial and riverine floods, increased average and extreme temperatures, droughts, storm surges and sea level rise, among others (GCF,2023a)

	Potential impacts	What is the risk level at present?	Is the risk projected to change?	Mitigation measures
General infrastructure (including supporting infrastructure)				
Extreme Heat stress (human) [acute]	Heat stress that can affect the workforce. Work/rest cycles of the workforce might be affected.	**Very Low** in the present climate (2000-2019)	**Very Low-Low risk** for all scenarios, all projection periods. Sources: Climate Scale modelling. Confidence in projections: High (robust signal across models).	The risk of the WBGT overcoming thresholds that could cause heat stress affecting the workforce is projected to remain low. Therefore no mitigation measures are required.
Extreme Fire conditions [acute]	Damage to infrastructure due to wildfires.	**High risk** in the present climate (2000-2019)	**High risk** for all scenarios, all projection periods. Sources: Climate Scale modelling. Confidence in projections: High (robust signal across models).	This metric evaluates the meteorological conditions that favour the occurrence of wildfires, but does not take into account the fact that the actual fire risk is reduced if combustion material is not available in the site. The majority of the project area is covered in open space (wetlands and short grass), so taking into account that the vulnerability is low, the risk of wildfire can be downgraded to **low-medium.** However, due to the potential high risk of wildfire in the area, the design should consider vulnerability reducing measures, and adhere to international and national fire safety regulations for solar panels. Vulnerability can be reduced by regularly clearing vegetation in the area, and by incorporating fire detection and early warning systems.

Extreme precipitation (Flooding) [acute]	Pluvial and surface flooding as a result of extreme precipitation. Extreme precipitation can cause flash flooding and erosion of the infrastructure foundation.	**Low risk** in the present climate (2000-2019)	**Low** risk for all scenarios, all projection periods. <u>Sources</u>: Climate Scale modelling. <u>Confidence in projections</u>: High (robust signal across models).	Extreme precipitation is used as a proxy for pluvial and surface flooding**.** No risk is projected in the area of the project. Flood mitigation measures to build in resilience include: -appropriate site planning including drainage systems that could divert stormor runoff water away and flood barriers - Design assets with steel foundations -Mount vulnerable equipment above expected flood levels -Install substation flood protection and or elevate substations -Locate inverters in weather resistant shelters While this has a cost implication, it can ensure the design lifespan is realised while also promoting easier serviceability of PV systems.
Coastal inundation [acute]	Damage to coastal infrastructure due to sea level rise and storm surge.	**Low** in the present climate (2000-2019)	**Low risk** for all scenarios, all projection periods. <u>Sources</u>: Climate Scale modelling.	The 1 in 100-year return period Extreme Total Water Level is used as an indicator to identify coastal inundation risks. The infrastructure is planned to be located at more than 0.7km from the coast and more than 10m above sea level. Projected increases by 2050s in ETWL are no larger than 70 cm (considering uncertainty ranges and the three emissions' scenarios - see table 8) than the historical ETWL.
Water scarcity (hydrological and agriculture) [chronic]	Reduce water availability for different uses, in particular for PV panel cleaning.	**High risk** for hydrological droughts and **Medium risk** for agricultural droughts in the present climate (2000-2019)	**High** (SSP2-4.5 and SSP5-8.5) or **Medium-High** (SSP3-7.0) in the mid term (2040-2059) (Medium Confidence). **High or Medium-High risk** of **hydrological droughts** from the baseline onwards and all scenarios (High Confidence) <u>Sources</u>: Climate Scale modelling.	Ensure sufficient water capacity for cleaning as dust may worsen in longer dry spells. Incorporate panel cleaning approaches that require low water consumption.

Coastal erosion	Damage to coastal infrastructure.		**Low risk**, based on data from one modelling study (limited evidence-low confidence) and information about the project. RCP4.5 and RCP8.5 in 2050 with respect to 2010.	The ensemble median of the projected changes is -48m (with 90% range: -90m to -20m) for RCP4.5, and -50m (with 90% range: -110m to -10m) for RCP8.5. Because the area of the project is at least at about 700 metres from the coast, the reported values for shore retreat represent a low risk to the project.
Soil erosion [chronic]	Damage to infrastructure.	**Low** (only historical period available)		These hazards were derived from global data sets. A localised geotechnical study would be necessary to confirm the findings.
Subsidence [chronic]	Damage to infrastructure	**High** (only historical period available)		
Landslides [acute]	Damage to infrastructure	**Very Low** (only historical period available)		
PV Solar technology				
Extreme wind (storminess) [acute]	Damage to infrastructure due to extreme winds.	**Very Low** risk in the present climate (2000-2019)	**Very Low risk** in the short and medium projection periods and for all scenarios. Sources: Climate Scale modelling. Confidence: Medium	Extreme wind speeds are not projected to change significantly in this location (ensemble median of changes between -1.4% and 4.6% depending on scenario and projection period), with a large model spread (Low or Medium confidence in the direction of change). In all cases the projected intensities remain within the range of intensities corresponding to Low risk (see Appendix B). At concept and detailed design stages, build in resilience (robustness and redundancy) of ground-mounted PVs to strong winds, by carefully considering layout, orientation, and construction details. For instance half cut solar cells are less prone to micro-cracks due to their more compact structure and could be used to minimise the impacts of extreme winds and hail.

Hail [acute]	Damage to PV panels surface	**Very Low** (only historical period available)		The risk of hail in the baseline period is very low. However, climate models do not have the skill to project changes in hailstorms. Resilience could be built in by, for instance using half-cut sollar cells as mentioned above, or adding a protective cover to prevent hail damage.
Mean irradiation (GHI and DHI) - reduction [chronic]	Energy / Revenue Loss in revenue due to change in irradiation.	Baseline period is assumed to be at no risk.	**Very Low** or **Low risk** (reductions in irradiance less than 2%) for all scenarios . Sources: Climate Scale modelling. Confidence: Medium confidence	The risk of decreases in irradiation are projected to be low, so no mitigation measures are required (other than carrying out a sensitivity analysis in the financial model). In fact, projected changes are very close to cero (ensemble median) , and uncertainty ranges are within +-1%, changes dimmed to be small to represent a risk (when negative) or opportunity (when positive).
Mean Air Temperature - increase [chronic]	Energy / Revenue Loss in revenue due to chronic increases in temperature.	Baseline period is assumed to be at no risk.	**Low ris**k (increases less than 2C) with High Confidence for 2020-2039. For SSP3-7.0 and SSP5-8.5 the risk is **Low-Medium** for 2040-2059 with Medium confidence. Sources: Climate Scale modelling.	Even though annual average increases of mean air temperature are not projected to imply a risk for the efficiency of the panels, seasonal variations and extreme heat might have an effect. At concept and detailed design stages, build resilience by taking into account climate adjusted temperature design criteria for components to ensure durability and efficiency under increased average and extreme temperatures.
Mean wind speed@10m - reduction [chronic]	Energy / Efficiency Loss of revenue due to decrease in wind speed	Baseline period is assumed to be at no risk.	**Very Low or Low Risk** (reductions smaller than 1%) with Medium confidence. Sources: Climate Scale modelling.	The risk of a decrease in mean wind speed that could imply a loss in production due to temperature losses is projected to be low. Therefore no mitigation measures are required.
Days in heat wave condition	Energy / Revenue Loss in revenue due to chronic	Baseline period is assumed to be at no risk.	**Very Low Risk** (less than 100 days/year overcome the P90	The risk of having more than 100 days per year on average in extreme heat conditions is projected to be very low. Therefore no mitigation measures are required.

[chronic]	increases in days in extreme temperature conditions.		baseline temperature) with High confidence. Sources: Climate Scale modelling.	

Table 14: physical risks posed by climate change on general energy infrastructure and PV solar technology, together with proposed high-level adaptation measures

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Appendix A: Data and modelling approach

Observational data

The information for the baseline period (2000-2019) is based on the ERA5 reanalysis.
ERA5 is the fifth generation of the European Center for Medium Range Weather Forecast (ECMWF) atmospheric reanalysis of the global climate, covering the period from 1940 to present [Hersbach et al 2020]. The essential climate variables analysed include:

- daily maximum, minimum and mean temperature, and dew temperature
- daily accumulated precipitation
- daily 10 and 100m wind speed max daily wind and 10 minutes wind gust
- daily global horizontal irradiance (GHI)
- significant wave height

ERA5 daily wind speeds and irradiance are recalibrated to 3km resolution using Vortex data.

Climate model projections

Projected changes in the climate variables are obtained using an ensemble of Global Climate Models(GCMs) or Earth System Models (ESMs) generated by climate modelling centres from around the World, and archived by the Coupled Model Intercomparison Project 6 (CMIP6) [Eyring 2016]. Models' projections are analysed for four Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5)[Riahi et al, 2017)]. The Climate Scale modelling system samples two sources of uncertainty in climate models' projections: climate model formulation and climate forcing uncertainties, by considering an ensemble of climate models and different forcing scenarios respectively. The uncertainty information is summarised in the tables by including not only the median of the ensemble of changes, but also the uncertainty range classified as likely in the IPCC guidance. This is defined as the range that encloses 66% of the models' changes, i.e., the 17%-83% range [IPCC 2010].

Climate model data for the period 1980-2099 is analysed. Climate model simulations for up to the year 2014 were run with historical values of greenhouse gases and other forcing agents. From 2015 onwards data corresponding to SSPs scenarios are considered.

The essential climate variables include:

- daily maximum, minimum and mean temperature
- daily accumulated precipitation
- daily 10 m wind speed
- daily global horizontal irradiance (GHI)
- daily specific humidity

The number of models included varies depending on the climate variable and the SSP scenario considered. There are, for instance, between 20 and 24 models for temperature related variables, 23 for precipitation and 20 for wind.

Downscaling climate models

The typical spatial resolution of Global Climate models varies between 100 and 200 km. In order to increase the resolution and at the same time correct biases in model projections, a statistical approach based on the quantile mapping technique is employed [Cannon 2018]. This approach was specifically designed to preserve trends and changes simulated by climate models in response to anthropogenic forcings. The majority of the simulated climate variables are downscaled to 25km2 resolution using ERA5 as a representation of the observed climate, ensuring a globally consistent dataset for multiple variables simultaneously. In the case of wind speeds, ERA5 recalibrated with Vortex data to 3km2 resolution is employed for the downscaling.

The downscaled projections are then used to estimate projected changes in climate variables for different horizons in the future, the underlying assumption being that even if model simulations have biases, the projected changes are robust.

Once the downscaled time series of a set of essential climate variables (max, min, mean temperature, precipitation, relative humidity, GHI and wind speed at 10m and 100m) are obtained, other derived metrics such as fire weather indices, or drought and extreme precipitation indices can be calculated. The table below lists the climate metrics available in the Climate Scale REPORT.

Hazard Metric	**Metric Category**	**Type**	**Technology**	**Definition**
Mean Daily Temperature	Temperature Related	Chronic	General	Average of daily time series of mean temperature over the specified time horizon.
Max Daily Temperature	Temperature Related	Chronic	General	Average of daily time series of max temperature over the specified time horizon.
Min Daily Temperature	Temperature Related	Chronic	General	Average of daily time series of min temperature over the specified time horizon.
Heat Wave Index	Temperature Related	Acute	General	Average number of days per year in heat wave conditions, as defined by the Warm Spell Duration Index (WSDI). The WSDI is the count of days in a span of at least six days where the maximum daily temperature is above the 90th percentile of the baseline daily max temperature distribution. This distribution is computed using a 5 days running mean.
Cold Wave Index	Temperature Related	Acute	General	Average number of days per year in cold wave conditions, as defined by the Cold Spell Duration Index (CSDI). The CSDI is the count of days in a span of at least six days where the minimum daily temperature is below the 10th percentile of the baseline daily min temperature distribution. This distribution is computed using a 5 days running mean.
Icing Days Index	Temperature Related	Chronic	General	Average number of days per year where daily maximum temperature drops below 0ºC.
Cold Days Index	Temperature Related	Chronic	General	Average number of days per year where daily minimum temperature drops below 0ºC.

Warm Days Index	Temperature Related	Chronic	Solar	Average number of days per year where daily maximum temperature is higher than 25ºC.
Hot Days Index	Temperature Related	Chronic	Solar	Average number of days per year where daily maximum temperature is higher than 40ºC.
Wet Bulb Globe Temperature (WBGT) Acute	Temperature Related	Acute	General	Average number of days per year where the WBGT (*) index overcomes 28ºC, selected as the threshold cut-off value for heavy labour being limited to 50% of the time.
Wet Bulb Globe Temperature (WBGT) Chronic	Temperature Related	Chronic	General	Average value of the WBGT (*) index over the three hottest months of the year. For each location, the three hottest months are chosen as the three consecutive hottest months in the ERA5 climatology over the period 1980-2019.
Fire Weather Index Acute (FWI)	Temperature Related	Acute	General	Measure of acute changes in fire danger. It indicates how the number of days over a (baseline) extreme value of FWI (**) changes in time. The baseline extreme value is defined as the fire intensity that is overcome 5% of the days over the baseline period. This value is shown in the "Reference" column. The values presented in the projection horizons indicate the % of days that the FWI overcomes the value reported in the "Reference" column..
Fire Weather Index Chronic	Temperature Related	Chronic	General	Measure of chronic changes in fire danger, estimated by computing the average value of the FWI (**) over the days when the fire intensity is larger than 11.2 in each individual year. The values shown in each period, including the baseline, are the mean of that yearly time series over each reported period.
Mean Daily Precipitation	Water Related	Chronic	General	Average of daily accumulated precipitation time series over the specified time horizon.
Agricultural Drought Index	Water Related	Acute	General	Number of months per period in agricultural drought condition, i.e. when the 3 month-SPEI (***) is smaller than -1.65.
Hydrological Drought Index	Water Related	Acute	General	Number of months per period in agricultural drought condition, i.e. when the 12 month-SPEI (***) is smaller than -1.65.
Extreme Precipitation	Water Related	Acute	General	Magnitude of the accumulated daily precipitation with 1 in 50 years return period. This is obtained by fitting an extreme value distribution to the annual maxima of daily accumulated precipitation over the specified time horizon.
Consecutive Dry Days	Water Related	Chronic	General	Average of the annual maximum number of consecutive days with precipitation of less than 1 mm. This index is a measure of low precipitation, with high values corresponding to long periods of low precipitation and potentially drought-favouring conditions. An increase of this index with time means that the chance of drought conditions will increase.

Consecutive Wet Days	Water Related	Chronic	General	Average of the annual maximum number of consecutive days with precipitation of more than 1 mm. This index is a measure of high precipitation, with high values corresponding to higher chances of flooding. An increase of this index with time means that the chance of flood conditions will increase.
Mean Daily GHI	Radiation Related	Chronic	Solar	Average of daily time series of Global Horizontal Irradiance (GHI).
Mean Daily DHI	Radiation Related	Chronic	Solar	Average of daily time series of Diffuse Horizontal Irradiance (DHI) over the specified time horizon. Daily values of DHI are estimated from GHI using the Collares-Pereira and Rabl approach [Collares-Pereira 1979].
Mean Daily Wind Speed @10	Wind Related	Chronic	General	Average of daily time series of 10m wind speed.
Mean Daily Wind Speed @100	Wind Related	Chronic	Wind	Average of daily time series of 100m wind speed over the specified time horizon.
Air Density	Wind Related	Chronic	Wind	Average of daily air density over the specified time horizon. Daily values of air density are computed from combining temperature with surface pressure.
Extreme Wind Speed (Vref)	Wind Related	Acute	Wind	Maximum daily hourly wind speed @100m with 1 in 50 years return period. This is obtained by fitting a Gumbel distribution to the annual maximum hourly wind speed of the ERA5 recalibrated data at 3km resolution for the baseline value. Projections are obtained by using a transfer function between model daily wind speeds and observed maximum daily hourly wind speeds. The transfer function assumes that changes in maximum daily hourly wind speeds follow the changes in the statistical distribution of wind@10m projected by the climate models.
Sea Level Rise	Ocean Related	Chronic	General	CMIP5: Sea level rise in the projection periods is obtained from the database described in Church et al (2013) and Carson et al (2016). It includes the effects of the thermal expansion of the oceans and contributions from glaciers, Greenland and Antarctic ice sheets, and land water storages. For a particular location, the sea level rise shown in the projection periods is the value of the nearest neighbour ocean point in the Church data set. This data set does not include the effects of tides and storm surges. Changes represent the increase in sea level with respect to the 1986-2005 baseline period. CMIP6: Projection data from the IPCC 6th Assessment Report](AR6) (Fox-Kemper et al 2021)[6]

[6] Sea level rise data was sourced from https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report

				Changes represent increase in sea level with respect to the 1995-2014 period. The projections include the same contributions to sea level rise as for the CMIP5 dataset. Baseline information is obtained from the C3S sea level products which are time series of gridded Sea Surface Height and derived variables obtained by merging two satellite altimetry measurements [C3S 2020]. The reference period is 1993-2012.

(*) The Wet-Bulb Globe Temperature (WBGT) is an accepted international standard for the assessment of heat stress, that captures the combined effects of air temperature, humidity, wind and radiative forcing on heat transfer between the environment and the human body. The International Standards Organisation (ISO) sets guidelines to keep core body temperature at 38°C. It uses WBGT as the heat stress index to specify recommended rest/work cycles at different physical work intensities (ISO Standard 7243). We use the formulation of Lemke et al (2012) to calculate the outdoor WBGT.

(**) The Fire Weather Index (FWI) is a meteorologically based index that estimates potential fire intensity per unit length of fire front based on weather conditions [Van Wagner 1987]. The fire intensity, and therefore the FWI are unitless. Fire danger is classified by the European Forest Fire Information System (EFFIS) as Very low: <5.2, Low: 5.2 - 11.2, Moderate: 11.2 - 21.3, High: 21.3 - 38.0, Very High: 38.0 - 50, Extreme: >50.

(***) The Standardised Precipitation Evapotranspiration Index (SPEI) measures the climatic water balance (precipitation minus evapotranspiration) at different time scales [Vicente-Serrano 2010]. The SPEI index is computed for 3 and 12 month duration droughts to indicate the risk of agricultural and hydrological droughts respectively. Monthly values of SPEI smaller than -1.65 indicate water stress.

Appendix B: Estimation of risks

The term 'physical climate risk' can be conceptualised as the combination of the potentially damaging physical event or hazard (e.g. flood), the exposure of people or assets to these variations (e.g assets built in flood prone areas), and their vulnerability (e.g. no flood protection measures).

In this report physical risks refer only to the hazard component of the risk. Vulnerability and exposure of the assets are not taken into account when assigning the risk levels. For instance, wildfire risk considers only the meteorological conditions favouring the occurrence of wildfires, without taking into account other factors such as the characteristics of the surrounding environment (is there vegetation that can serve as fuel?), or the existence of protective measures already in place.

Climate change impacts materialise through acute changes or extreme events, and through secular or chronic changes.

In the case of acute changes, the intensity and magnitude, frequency, duration, timing and spatial extension of a region's acute climate hazards could be altered.

In the REPORT, acute risks metrics take into account two of these dimensions, intensity and frequency. The levels of risk associated with changes in intensity and in frequency of extreme events are combined into a unique level of risk for each acute hazard.

Chronic risk metrics correspond to variables that change monotonically, such as for instance continuous increases of mean air temperature or mean sea level. For most of these metrics the level of risk is linked to percentage changes of the metric with respect to the historical period 2000-2019. Other chronic metrics, like Annual Precipitation, express the average value of a metric in absolute terms.

For any location the following risk indicators, potentially relevant for any type of infrastructure, are included:

Temperature related.

- Heat stress (for humans): as indicated by combined changes in frequency and intensity of extreme values of daily Wet-Bulb Globe Temperature (WBGT), when impacts on human health are felt.
- Fire conditions: as indicated by combined changes in frequency and intensity of extreme values of the daily Fire Weather Index (FWI), when meteorological conditions favour the occurrence of wildfires.

Water and precipitation related.

- Extreme precipitation (Flooding): as indicated by combined changes in frequency and intensity of the extreme accumulated daily precipitation, as a proxy for pluvial and surface flooding. Note that flooding is strongly dependent on other factors, apart from the meteorological conditions. Therefore additional information beyond that provided by climate models should be used to compute the overall risk of flooding.
- Water scarcity: as indicated by changes in the number of months in drought conditions for

hydrological and agricultural droughts. Note that to estimate water stress, information about water demand is also required.

- Hail storms: as indicated by the average annual probability (in days/year) of hail with a diameter >2.5 cm, normalised to areas of 100 km x100 km, for 1979–2015 (Prein et al, 2018).

  Wind related.

- Extreme wind (Storminess): as indicated by combined changes in frequency and intensity of the extreme values of daily wind speed at 10m, when damage to infrastructures can occur.
- Tropical cyclones: as indicated by extreme wind speeds associated with the occurrence of Tropical cyclones. Only information for the baseline period is provided based on synthetic tropical cyclones data (Bloemendaal et al, 2020).

  Soil related.

- Subsidence: based on dataset "Mapping the global threat of land subsidence" (Herrera Garcia et al, 2021) .
- Landslide: based on the World Bank Global Landslide Hazard Map.
- Erosion (Croplands): as indicated by the soil displacement by water erosion (Borrelli et al.,2022).

Depending on the asset type assigned to the location (e.g, Wind Energy) additional technology specific risk metrics are included. These metrics are either slightly different definitions of the damaging events considered for general infrastructures, adapted to represent hazards on the specific technology infrastructure (e.g, extreme wind speeds for wind turbine class identification), or chronic hazards that have the potential to impact on resource availability and/or operations & maintenance.

For the projection period, the risk level assigned to each metric is, unless otherwise stated, defined using the ensemble of downscaled climate models. Given a climate hazard/metric, for each model simulation, projection period and emissions' scenario, the risk category is computed. The possible risk categories include: very low, low, medium and high.

Due to the uncertainty in climate model projections, in some cases different models project different risk categories for the same scenario and projection period. To take into account this uncertainty, an overall risk level and a level of confidence in the projections is assigned using the criteria shown in the table below.

Confidence Levels		Definition
HC	High Confidence	when >80% models fall in the same category
MC	Medium Confidence	when between 60% and 80% of the models fall in the same category or more than 60% of the models fall across two contiguous categories
LC	Low Confidence	when none of the above is satisfied
	Risk Levels	**Maximum level of confidence achievable**

	High	HC
	Medium-High	MC
	Medium	HC
	Low-Medium	MC
	Low	HC
	Very Low-Low	MC
	Very Low	HC

In this way, the risk category can be used to identify sites that are threatened by different hazards, or might be in the future, while the level of confidence offers an indication of how robust this projection is according to the ensemble of climate models considered in the analysis.

Risks metrics for general infrastructure

Acute risks

Climate metric	**proxy for**	**Intensity based risk**		**Frequency based risk**		**Risk**
		Intensity that causes damage	**Probability thresholds**	**Frequency that causes damage**	**Intensity thresholds**	
Extreme Heat Stress (Human) WBGT	**Heat stress: Impact of heat on humans (*)**	28C	1 in 100 years 1 in 20 years 1 in 5 years	1 in 20 years	25C 28C 32C	Low Medium High
Extreme Fire Conditions FWI	**Extreme fire conditions(**)**	38	1 in 30 years 1 in 10 years 1 in 2 years	1 in 10 years	21 38 50	Low Medium High
Extreme precipitation (flooding)	**Pluvial and surface flooding**	100 mm/day	1 in 100 years 1 in 20 years 1 in 5 years	1 in 20 years	50 mm/day 100 mm/day 150 mm/day	Low Medium High
Extreme wind @10m Storminess	**Storminess: Wind damages (***)**	27 m/sec	1 in 100 years 1 in 20 years 1 in 5 years	1 in 10 years	19 m/sec 27 m/sec 31 m/sec	Low Medium High
Tropical Cyclones	**Wind damages**	33 m/sec	1 in 100 years 1 in 20 years 1 in 5 years	1 in 20 years	27m/sec 33 m/sec 39 m/sec	Low Medium High

(*) thresholds chosen following Thinkhazard! (https://thinkhazard.org/en/)

(**) thresholds chosen to cover the fire danger levels starting at high, as classified by the European Forest Fire Information (very low: <5.2, low: 5.2 - 11.2, moderate: 11.2 - 21.3, high: 21.3 - 38.0, very high: 38.0 - 50, and extreme: >=50.0)

(***) The wind speed thresholds are chosen to separate tropical storms (wind speeds 18-32m/s), and category 1 tropical cyclones (wind speeds 33-42m/s).

Chronic risks

		Risk Levels		
Climate metric	**Proxy for**	**Low**	**Medium**	**High**
Hydrological drought	**Water scarcity**	0 to 3% months in drought conditions	3 to 6%months in drought conditions	More than 6% months in drought conditions
Agricultural drought	**Water scarcity**	0 to 4% months in drought conditions	4 to 8% months in drought conditions	More than 10% months in drought conditions
Hail storms	**Hail storm damages**	1.5 to 2.5 days in a 100Km² area with more than 50% probability of occurrence of hail storm.	2.5 to 3.5 days	More than 3.5 days

Soil variables

Risks associated with subsidence, landslides and soil erosion are reported for the historical period using data from the following external sources:

metric	source	comments	RISK LEVELS
subsidence	Herrera Garcia et al (2021) Mapping the global threat of land subsidence, Science, 371 (6524), DOI: 10.1126/science.abb8549	Potential subsidence is calculated as a combination of the susceptibility of a location to experience subsidence and the probability of groundwater depletion.	The dataset provides risk levels from 1 to 6 that have been grouped as: Very Low 1 Low 2 Medium 3, 4 High 5, 6
landslides	World Bank Global Landslide Hazard Map. https://datacatalog.worldbank.org/search/dataset/	Estimated annual frequency of significant landslides per square kilometre. Significant landslides are those which are likely to have been	Landslide annual frequency is divided into risk categories using the following thresholds:

	0037584, last update:Apr 29, 2021	reported had they occurred in a populated place; limited information on reported landslide size makes it difficult to tie frequencies to size ranges but broadly speaking would be at least greater than 100 m2. The data provides frequency estimates for each grid cell on land between 60°S and 72°N for landslides triggered by seismicity and rainfall.	Very Low < 0.0001 Low 0.0001 - 0.001 Medium 0.001 - 0.01 High > 0.01 Units in yr-1
soil erosion (croplands)	Borrelli et al.,2022. GloSEM: High-resolution global estimates of present and future soil displacement in croplands by water erosion. Scientific Data (9), Article number: 3	High-resolution global estimates of soil displacement by water erosion obtained using the Revised Universal Soil Loss Equation based Global Soil Erosion Modelling (GloSEM) platform under present (2019) climate. GloSEM takes into account regional farming systems, the mitigation effects of conservation agriculture (CA), and climate change projections.	Soil erosion rates are divided into risk categories, according to the European Soil Bureau classification: Very Low: < 0.2 Low: 0.2 - 5 Medium: 5 - 20 High: > 20 Units in (Mg ha−1 yr−1)

Risk metrics for **solar assets**

Acute risks

Climate metric	**Risk**	**Intensity based risk**		**Frequency based risk**		
		Intensity that causes damage	**Probability thresholds**	**Frequency that causes damage**	**Intensity thresholds**	
Extreme wind@10m	O&M - Downtime Repair cost	33 m/sec	1 in 100 years 1 in 20 years 1 in 5 years	1 in 20 years	27 m/sec 33 m/sec 39 m/sec	Low Medium High

Chronic risks

		Risk Levels		
Climate metric	**Impact**	**Low**	**Medium**	**High**
Mean irradiation (global horizontal	Energy/Revenue	0 to -2 %	-2 to -4%	< -4%

irradiance-GHI, and diffuse horizontal irradiance-DHI)- reduction				
Daylight Air Temperature - increase	Energy/Revenue	0 to 1C	1C to 2C	More than 2C
Increase in number of cold days (min temp<-25C) [chronic]	Energy / Revenue	20 to 40 days/year	40 to 80 days/year	More than 80 days per year
Increase in number of heatwave days [chronic] Increase in the % of days with daily max temperature larger than the baseline P90.	Energy / Revenue	0 to 100 days/year	More than 100 days	NA
Mean wind speed@10m - reduction	Energy/ Efficiency	0 to -1 %	< -1%	NA

Appendix C: Glossary

CMIP5 (CMIP6) or Coupled Model Intercomparison Project 5 (6) is a climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP5 data set includes projections using the Representative Concentration Pathways. The CMIP6 phase includes projections using the SSPs as well as an ensemble of CMIP-endorsed model intercomparison projects (MIPs).

Earth System Models (ESM) is a coupled climate model that also explicitly models the movement of carbon through the earth system.

ERA5 is the European Centre for Medium Range Weather Forecast (ECMWF) reanalysis. It provides hourly estimates of a large number of atmospheric, land and oceanic climate variables covering the Earth on a 25km grid.

Global Climate Model (GCM) or **coupled climate model** is a computer code that estimates the solution to differential equations of fluid motion and thermodynamics to obtain time and space dependent values for temperature, winds and currents, moisture and/or salinity and pressure in the atmosphere and ocean. Components of a climate model simulate the atmosphere, the ocean, sea, ice, the land surface and the vegetation on land and the biogeochemistry of the ocean.

Reanalysis : a climate reanalysis combines observations and a numerical model that simulates one or more aspects of the Earth system, to generate a numerical description of the recent climate. This includes all locations on earth, and spans long time periods that can extend back several decades.

RCP or Representative Concentration Pathways are scenarios that include time series of emissions and concentrations of greenhouse gases and aerosols and chemically active gases, as well as scenarios of land use/land cover changes over the 21st century. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises the fact that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest. RCPs were used to develop climate projections in CMIP5.

- **RCP8.5** corresponds to an end of century warming in the range of 3.2-5.4C, and little or no policy changes resulting in unabated emissions. This is a high pathway which leads to a radiative forcing of 8.5 W m-2 in 2100.
- **RCP4.5** corresponds to an end of century warming in the range of 1.7-3.2C, and relatively ambitious emissions reductions with emissions peaking by 2040. This is a stabilisation pathway in which radiative forcing is limited at approximately 4.5 W m-2 in 2100.
- **RCP2.6** corresponds to end of the century warming of 2C, with emissions starting to decline at around 2020. The radiative forcing peaks at approximately 3 W m-2 and then declines to be limited at 2.6 W m-2 in 2100

SSP or Shared socio-economic pathways were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation. Based on five narratives, the SSPs describe alternative socio-economic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fuelled development (SSP5), and a middle-of-the-road development (SSP2). SSP1 and SSP5 envision relatively optimistic trends for human development, with "substantial investments in education and health, rapid economic growth, and well-functioning institutions". They differ in that SSP5 assumes this will be driven by an energy-intensive, fossil fuel-based economy, while in SSP1 there is an increasing shift toward sustainable practices. SSP3 and SSP4 are more pessimistic in their future economic and social development, with little investment in education or health in poorer countries coupled with a fast-growing population and increasing inequalities. SSP2 represents a "middle of the road" scenario where historical patterns of development are continued throughout the 21st century.

The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections provides an integrative frame for climate impact and policy analysis.

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