

The impact of climate change on the future of solar energy

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Introduction

Solar energy has grown constantly over the last few decades, while the first solar plants only appeared 40 years ago, solar energy has now captured a big part of the electrical grid. Solar energy is essential for the current energy transition as it is one of the most globally used sources of renewable energy only behind hydropower and wind¹.

In our current global pursuit for electrification to avoid the diminishing fossil fuels and their damaging effects, solar is one of the market leaders. Solar energy is not only carbon free but it is less disruptive to its surroundings than wind energy and hydropower, which are renowned for disrupting natural ecosystems. Solar energy has the crucial advantage that it can be used domestically to empower homeowners to become energy independent. For these reasons, it is estimated that 20% of EU's electricity demand will be met by solar energy in 2040².

Nevertheless, solar energy still has a lot of work ahead to improve its relatively low efficiency of around 25%³. Unfortunately, solar energy will face the consequences of the problem it is trying to resolve: climate change. This climate change paradox highlights that while solar energy is fighting climate change, at the same time, climate change can reduce its effectiveness. Factors such as extreme weather can reduce solar panel performance and reduce their lifespan.

It is undeniable that climate change is reshaping the earth in unimaginable ways, in turn affecting our daily life. In fact, according to recent IPCC's reports (Intergovernmental Panel on Climate Change), natural disasters fuelled by climate change are already worse than scientists originally predicted. Despite the signature of many climate change agreements, such as the Paris Agreement, we are not on track to meet any of the goals proposed in those agreements. Under the Paris Agreement (2015)⁴ global temperatures should not exceed 2°C from pre-industrial levels and ideally 1.5°C, an increase we are on the verge of reaching 10 years later.

¹ October 2024 International Energy Agency (IEA) Renewables 2024 <https://www.iea.org/reports/renewables-2024/global-overview>

² September 2022 Directorate-General for Energy (European Commission) In focus: Solar energy-harnessing the power of the sun https://commission.europa.eu/news-and-media/news/focus-solar-energy-harnessing-power-sun-2022-09-13_en

³ July 2025 Jason Svarc (Clean Energy Reviews) Most efficient solar panels 2025 <https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels>

⁴ May 2022 (Carl-Friedrich Schleussner, Alexander Nauels, Uta Klönn, Bill Hare) (Climate Analytics) Understanding the Paris Agreement's Long-Term Temperature Goal <https://climateanalytics.org/comment/understanding-the-paris-agreements-long-term-temperature-goal>

Climate change is no longer a distant threat, it is clearly noticeable nowadays: sea levels are rising, glaciers and polar sheets are melting, sea temperatures are rising. These changes are increasingly dangerous as higher sea and ambient temperature (2023 was the hottest year for ocean heat content in recorded history)⁵, are increasing the intensity of hurricanes and making heavy rainfall more likely. In fact, according to multiple studies, the number of Category 4 and 5 hurricanes in the North Atlantic has nearly doubled since 1970⁶. Floods, droughts and wildfires are growing in scope and severity and the number of climate refugees too; according to the IEP (Institute for Economics and Peace) 1.2 billion people could be displaced globally by 2050⁷.

Climate change will have transversal effects; global annual damages from climate change were around \$229 billion⁸ (USD) in 2024 and are expected to rise to trillions per year in the following decades. More recurrent and intense heatwaves are taking more lives every year, 61,000 people died in Europe from heat stroke in the Summer of 2022⁹.

Market

Current market

As of mid 2025 global installed solar capacity was of over 2.2 terawatts (TW) and 0.6 TW were added in 2024¹⁰ alone, showing the rapid pace with which solar energy is expanding. Solar energy is showing no signs of slowing down and some estimates state that 1TW of solar energy could be added each year by 2030. Most of the new installed capacity comes from China, which installed around 55% of the new solar capacity in 2024. China has become a major player in this industry since the late 2010s, when they overtook the EU to become the world's leader in solar energy over the US.

Market evolution

The market had been historically dominated by the US, EU and Japan as they were responsible for a big part of the advances in solar energy and its adoption. Many European countries, such as Germany¹¹ and Spain, introduced aggressive feed-in tariffs (FiTs) in the early 2000s making solar profitable for many households. These FiTs gave fixed electricity prices, sometimes above market rates, to solar energy producers for

⁵ January 2024 NOAA 2023 was the world's warmest year on record, by far <https://www.noaa.gov/news/2023-was-worlds-warmest-year-on-record-by-far>

⁶ March 2024 Aaliyah Uteuova (The Guardian) Hurricanes are intensifying more rapidly-and the most vulnerable communities are hit the hardest <https://www.theguardian.com/us-news/2024/mar/07/hurricane-strength-global-warming-intensification>

⁷September 2020 Jon Henley (The Guardian) Climate crisis could displace 1.2 billion people by 2050, report warns <https://www.theguardian.com/us-news/2024/mar/07/hurricane-strength-global-warming-intensification>

⁸December 2024 Jonathan Watts (The Guardian) 2024's most costly climate disasters killed 2,000 people and caused \$229bn in damages data shows <https://www.theguardian.com/environment/2024/dec/30/2024s-most-costly-climate-disasters-killed-2000-people-and-caused-229bn-in-damages-data-shows>

⁹ July 2023 Joan Ballester (Nature Medicine) Heat-related mortality in Europe during the summer of 2022 <https://www.nature.com/articles/s41591-023-02419-z>

¹⁰ May 2025 (Solar Power Europe) Global Market Outlook for Solar Power 2025-2029 <https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029/detail>

¹¹ (Wikipedia) German Renewable Energy Sources Act https://en.wikipedia.org/wiki/German_Renewable_Energy_Sources_Act

each unit energy they sent to the grid. These aggressive tactics helped solar technology scale, in turn lowering global solar prices. As solar energy's affordability grew, these tariffs were gradually phased out and reduced due to their economic unviability in-early 2010s¹².

The 2010s saw the rise of new countries in the sector such as China and India. By 2010¹³ China became the world's leader in solar panel production and by 2013 it became the world's largest installer of solar photovoltaic (PV)¹⁴; China produces around 80%¹⁵ of the world's solar panels nowadays. The full dominance of the supply chain, ambitious governmental targets, and an enormous energy demand has made China the world's new solar superpower. Furthermore, the rate of solar power proliferation is unmatched as China has already beaten its ambitious plans for 2030¹⁶ regarding solar energy. Both India and China are using solar energy as their main weapon to decarbonise while still ensuring economic development. In 2025, 10 of the 15 largest solar plants are in India or China¹⁷, highlighting how these relatively new players have taken over the market.

Outlook in main markets

Solar energy has a bright future ahead, as many regions of immense potential such as those in the Middle East or South America remain unexploited or are undergoing construction of megaprojects. We can be certain that China will continue to be the world's global solar power despite the significant investments from other countries, not only due to its big head start but also due to its heavy investment in new solar technologies and clear governmental vision. China is currently investing in the development of perovskites solar cells, which are cheaper, lighter, ultra-thin and more efficient than the conventional silicon-based cells¹⁸.

If China successfully develops and commercialises these new cells, it could further enhance its position as the global solar superpower. Unlike China, the US is facing political uncertainty, which will not allow it to become the solar energy superpower it once was.

¹² 2016 (Cambridge Judge Business School) Spain's Solar PV Boom and Bust <https://www.jbs.cam.ac.uk/wp-content/uploads/2024/04/eprg-wp1603.pdf>

¹³ January 2010 Keith Bradsher (Research Gate) China Leading Global Race to Make Clean Energy https://www.researchgate.net/publication/265082255_China_Leading_Global_Race_to_Make_Clean_Energy

¹⁴ January 2014 Stephen Lacey (Green Tech Media) China may have deployed more solar in 2013 alone than America has installed altogether <https://www.greentechmedia.com/articles/read/china-deployed-more-solar-in-2013-than-america-has-installed-all-time> January 2014 Stephen Lacey (Green Tech Media) China may have deployed more solar in 2013 alone than America has installed altogether <https://www.greentechmedia.com/articles/read/china-deployed-more-solar-in-2013-than-america-has-installed-all-time>

¹⁵ June 2022 IEA The world needs more diverse solar panel supply chains to ensure a secure transition to net zero emissions <https://www.iea.org/news/the-world-needs-more-diverse-solar-panel-supply-chains-to-ensure-a-secure-transition-to-net-zero-emissions>

¹⁶ October 2023 AFRY China expects to achieve its 2030 wind and solar ambitions ahead of schedule in 2025 <https://afry.com/en/insight/china-expects-achieve-2030-wind-and-solar-ambitions-ahead-in-2025>

¹⁷ March 2024 Tom Gill (The Eco Experts) The world's biggest solar farms <https://www.theecoexperts.co.uk/solar-panels/biggest-solar-farms>

¹⁸ January 2025 Jiye Han (Nature) Perovskite solar cells <https://www.nature.com/articles/s43586-024-00373-9>

On July 4th 2025 Trump signed the “Big Beautiful Bill”, which phased out¹⁹ most of the initiatives presented by the Inflation Reduction Act (August 2022) of the Biden presidency. Under the Inflation Reduction Act²⁰, \$370 billion were being destined for energy security and climate programs over 10 years, this act provided major tax credits for the development of solar farms making solar a very attractive source of energy. As a result of the “Big Beautiful Bill” solar energy no longer benefits from these tax incentives²¹, unless these projects meet infeasible and extremely strict timelines, putting their target of net zero by 2050 under serious risk. The foreseeable great decrease in investment in the second largest solar power, the US, will have cascading effects across the entire global market: many foreign companies will move these projects elsewhere and most likely to Eurasia.

The unfavourable conditions and increased risk now present in the US are the same reasons why investors tend to avoid Africa²² and South America for the development of their solar farm projects, despite their immense solar potential. However, poor grid infrastructure and high financing risk tend to be the major deciders when companies choose not to construct solar farms in these continents. In general, due to increased risk and global political instability, solar energy projects are more likely to concentrate in countries where they already have an extensive track record such as European countries.

European countries have doubled down on their investment in renewables, particularly in solar, as the war on Ukraine has put on halt the supply of Russian gas and oil, prompting EU countries to become energy sovereign²³. For these reasons, the European Union launched a plan named REPowerEU in May 2022 mobilising close to €300 billion, which includes very aggressive policies to ensure the spread of solar energy.

This includes the European Solar Rooftops Initiative²⁴, which will require new public and commercial buildings to install rooftop solar by 2027, new residential buildings by 2030 and all suitable existing public buildings by 2031, providing an estimate of 25%²⁵ of all European electricity demand. Furthermore, under this plan the EU wants to return the supply chains of solar panels to Europe and accelerate solar panels permits. This aggressive regulation aims for Europe’s solar capacity to triple in a decade to 600GW in

¹⁹ July 2025 (Latham and Watkins) One big, beautiful bill: new law disrupts clean energy investment <https://www.lw.com/en/insights/one-big-beautiful-bill-new-law-disrupts-clean-energy-investment>

²⁰ August 2022 (Bipartisan policy) Inflation Reduction Act Summary https://bipartisanpolicy.org/download/?file=/wp-content/uploads/2022/08/Energy-IRA-Brief_R04.pdf

²¹ July 2025 Brian Lynch (solar.com) Trump and the Fate of the 30% Solar Tax Credit in 2025 <https://www.solar.com/learn/trump-and-the-fate-of-the-30-solar-tax-credit/>

²² April 2025 (World Economic Forum) Unlocking clean energy investment: Overcoming perceived risks in emerging markets <https://www.weforum.org/stories/2025/04/unlocking-clean-energy-investment-in-emerging-markets/>

²³ May 2022 (European Commission) REPowerEU Affordable, secure and sustainable energy for Europe https://commission.europa.eu/topics/energy/repower_eu_en

²⁴ May 2024 (SolarPower Europe) EU Rooftop Solar Standard alone could solar power 56 million homes <https://www.solarpowereurope.org/press-releases/eu-rooftop-solar-standard-alone-could-solar-power-56-million-homes>

²⁵ May 2022 (European Commission) EU Solar Energy Strategy <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52022DC0221>

2030²⁶, setting up and providing the necessary help for European countries to become global solar superpowers.

Oceania, mostly Australia, is experiencing great growth in the solar energy industry as over 1/3 of Australian homes²⁷ are now powered by solar energy, due to Australia's great solar potential. In addition, Australia's political stability is attracting the attention of major investors, as Australia places itself as the energy exporter²⁸ of the region. For example, Australia is currently starting a project where it would send its excess solar energy via an undersea cable to Singapore²⁹; alternatively, Australia is also undergoing projects where it would use this excess solar energy to produce green hydrogen to be exported to countries like Japan or Korea³⁰. As the country with the highest solar generation per capita³¹, Australia is in a great position to become a global solar superpower as long as its infrastructure develops to meet such high demands. In addition, solar energy is being the key tool allowing small oceanic islands to become 100%³² renewable and energy independent.

From a global perspective, solar PV is now very close to having the lowest LCOE³³ (Levelised Cost of Energy) out of all energy sources, allowing solar energy to grow at an unprecedented speed. With technological advancements and economies of scale, solar energy's LCOE will continue to have a dramatic decline³⁴. Countries' supportive regulation and ambitious targets, along with the use of solar energy to ensure energy sovereignty is allowing solar energy to prosper. Growing consciousness towards climate change, regulatory pressure and ambitious corporate ESG targets is giving solar energy the necessary help to grow from 5% of the current global electricity generation to over 25%³⁵ by 2040 under ambitious low emissions scenarios.

Examples of climate change hazards and their impact

Solar energy can be affected by a wide variety of factors, such as high/ low temperatures, climate variability, pollution or extreme weather. There is no doubt that climate change will shape the future of solar energy as it is already doing so. Prolonged

²⁶ May 2022 (European Commission) EU Solar Energy Strategy <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52022DC0221>

²⁷ November 2024 (Australian Department of Climate Change, Energy, the Environment and Water) Australia hits rooftop solar milestone <https://www.energy.gov.au/news/australia-hits-rooftop-solar-milestone>

²⁸ 2023 IEA (International Energy Agency) Australia 2023 Executive Summary Energy transition towards net zero <https://www.iea.org/reports/australia-2023/executive-summary>

²⁹ July 2024 George Heynes (Energy Storage News) Sun Cable Australia-to-Singapore renewable energy project wins transmission link approval <https://www.energy-storage.news/sun-cable-australia-to-singapore-renewable-energy-project-wins-transmission-link-approval/>

³⁰ April 2025 Antara Mascarenhas (The Diplomat) Australia and Japan's hydrogen partnership: navigating ambitions and realities <https://thediplomat.com/2025/04/australia-and-japans-hydrogen-partnership-navigating-ambitions-and-realities/>

³¹ April 2025 Andrew Blakers (Renew Economy) Chart of the day: Australia tops the world on solar generation per capita <https://reneweconomy.com.au/chart-of-the-day-australia-tops-the-world-on-solar-generation-per-capita/>

³² October 2013 (Solar Energy Industries Association) An island (Tokelau) powered 100% by Solar Energy <https://seia.org/news/island-tokelau-powered-100-solar-energy/>

³³ July 2022 (Pexapark) Levelised Cost of Energy (LCOE)-An overview <https://pexapark.com/blog/lcoe/>

³⁴ September 2023 (Alea Soft Energy Forecasting) The drop in the LCOE of renewable energies over the past decade drives the energy transition <https://aleasoft.com/drop-lcoe-renewable-energies-past-decade-drives-energy-transition/>

³⁵ 2018 (Statkraft) Renewables: Bright future for solar energy <https://www.statkraft.com/newsroom/news-and-stories/2018/renewables-bright-future-for-solar-energy/>

periods of cloud cover, higher ambient temperatures³⁶, aerosol production from more frequent wildfires³⁷ and increasing climate variability³⁸ are all factors that pose serious threats to solar panels' efficiency.

On the other hand, hazards such as more frequent extreme weather events³⁹ and increased lightning risk⁴⁰ pose direct threats to the life expectancy of solar panels. In general, solar panels are more influenced by climate change than society thinks; the melting of glaciers resulting in lower albedo and the ability of Earth to reflect sunlight can lower solar panels efficiency⁴¹ as warmer temperatures occur. To reiterate, climate change can affect solar panels life span and efficiency in many direct and indirect ways.

Global temperature increase

The most evident climate change hazards towards the future of solar energy are the increase in global temperatures. These have increased by 1.5°C⁴² from pre-industrial levels and the duration and intensity of heat waves have increased several times over⁴³. For example, 2023 was the hottest year on record according to NASA⁴⁴, until 2024 surpassed it, showcasing how global warming is showing no signs of slowing down.

These higher temperatures act as a double-edged sword for solar panels, as despite solar irradiance being higher, the efficiency of solar panels can be greatly reduced⁴⁵. Rooftop solar in cities is especially vulnerable due to the urban heat island effect, where surfaces like asphalt and concrete retain more heat. The optimum temperature for these panels is around 25°C and for every increase in 1°C the efficiency can drop from 0.4% to 0.5% following a linear trajectory until panel temperatures exceed 70°C. It is important to understand that panel temperatures are usually 20-25°C higher⁴⁶ than the surrounding air temperature on a sunny day due to heat absorption. This can be a particular problem in regions with very hot summers such as the Middle East, India, Australia, and Southwestern United States as temperatures of 40-45°C can result in efficiency losses of around 20%⁴⁷.

³⁶ February 2025 Pablo Gutiérrez (The Guardian) Two-thirds of the Earth's surface experienced record heat in 2024. See where and by how much - visualised <https://www.theguardian.com/environment/ng-interactive/2025/feb/20/two-thirds-of-the-earths-surface-experienced-record-heat-in-2024-see-where-and-by-how-much-visualised>

³⁷ (NASA) Wildfires and Climate Change <https://science.nasa.gov/earth/explore/wildfires-and-climate-change/>

³⁸ April 2025 Attracta Mooney (Financial Times) Climate graphic of the week: Sudden flips from hot to cold temperature come with climate change, says study <https://www.ft.com/content/3d7340bc-2900-49d5-b261-e442fa642e08>

³⁹ (IPCC) Chapter 11: Weather and Climate Extreme Events in a Changing Climate <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/>

⁴⁰ November 2014 Suzanne Goldenberg lightning strikes will increase due to climate change <https://romps.berkeley.edu/papers/pubdata/2014/lightning/guardian.pdf>

⁴¹ July 2024 Stephanie Safdie (Leaf by Greenly) What is the albedo effect and how does it impact global warming? <https://greenly.earth/en-gb/blog/ecology-news/what-is-the-albedo-effect-and-how-does-it-impact-global-warming>

⁴² January 2025 (Copernicus) Copernicus: 2024 is the first year to exceed 1.5°C above pre-industrial level <https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level>

⁴³ 2022 (World Meteorological Organisation) Heatwave <https://wmo.int/topics/heatwave>

⁴⁴ 2024 (NASA) Global Temperature <https://climate.nasa.gov/vital-signs/global-temperature/?intent=121>

⁴⁵ December 2024 Usman Noor (8M Solar) Solar panel efficiency vs temperature <https://8msolar.com/solar-panel-efficiency-vs-temperature/>

⁴⁶ December 2024 Usman Noor (8M Solar) Solar panel efficiency vs temperature <https://8msolar.com/solar-panel-efficiency-vs-temperature/>

⁴⁷ (Alusin Solar) What is the impact of temperature on the performance of solar panels? <https://alusinsolar.com/en/what-is-the-impact-of-temperature-on-the-performance-of-solar-panels/>

Furthermore, these high ambient temperatures also impact solar panels in early mornings, that are usually colder, but as solar panels can still retain some heat⁴⁸ from the previous day, they will start the day already with a lower efficiency. This thermal lag process can result in a vicious cycle for the panels as they are constantly overheating leading to their own degradation. Less efficient solar panels generate more heat, further reinforcing this feedback loop. In addition, this increase in temperatures does not only affect the solar panels but affects the system overall, as inverters are even more heat sensitive⁴⁹ than the panels and can be at risk of shutting down.

Moreover, in areas with consistently high temperatures, annual output can be considerably lower, maintenance costs can be higher and the solar panel lifespan could decrease⁵⁰. This problem will only be heightened as global temperatures continue to rise.

Extreme weather

Extreme weather, in particular hail, poses the greatest threat to the lifespan of solar energy installations. Hailstorms have increased in severity due to the increase in moisture in the atmosphere, as a warmer atmosphere includes up to 7%⁵¹ more moisture per °C. This has led to more instability in the atmosphere⁵² resulting in the formation of stronger convective storms making hail events more likely. At the same time, rising temperatures are increasing the atmospheric melting level⁵³, reducing the frequency of smaller hailstorms, as small stones will melt as they descend.

On the other hand, hailstone size will increase⁵⁴ due to the increase in moisture and various other factors such as wind shear. This will cause the formation of more “Hailstorm Alleys”, this is a region in Central America and Canada that experiences a high frequency of large damaging hailstorms with hailstones of more than 10cm in diameter. As a result, we can expect less hail events, but these events will be more damaging as they will contain fewer but larger stones⁵⁵.

Undoubtedly, this will have an extremely negative impact on solar panels as larger stones cause significantly more damage due to their increased mass and impact velocity. Despite many solar panels being labelled as hail resistant, those panels have

⁴⁸ January 2012 Witold Maranda The effect of thermal inertia in photovoltaic module simulation

https://www.researchgate.net/publication/241632771_The_effect_of_thermal_inertia_in_photovoltaic_module_simulation

⁴⁹ (Greentech Renewables) How does heat affect solar inverters? <https://www.greentechrenewables.com/article/how-does-heat-affect-solar-inverters>

⁵⁰ 2024 Olusola Bamsile The environmental factors affecting solar photovoltaic output

<https://www.sciencedirect.com/science/article/pii/S1364032124007998>

⁵¹ (Climate Signals) Atmospheric Moisture Increase <https://www.climatesignals.org/climate-signals/atmospheric-moisture-increase>

⁵² November 2023 Mike Nolan Study : Climate Change Has increased atmospheric instability over past 40 years <https://www.albany.edu/news-center/news/2023-study-climate-change-has-increased-atmospheric-instability-over-past-40-years>

⁵³ 2014 J.Dessens (Science Direct) Change in hailstone size distributions with an increase in the melting level height <https://www.sciencedirect.com/science/article/abs/pii/S016980951400266X>

⁵⁴ August 2024 Vittorio A. Gensini (Nature) Hailstone size dichotomy in a warming climate <https://www.nature.com/articles/s41612-024-00728-9>

⁵⁵ June 2025 Jannick Fischer (WTW) How hail is changing in Europe: 3 things to know about climate change and hail risk <https://www.wtwco.com/en-vn/insights/2025/06/how-hail-is-changing-in-europe-3-things-to-know-about-climate-change-and-hail-risk>

been tested with the smaller size of 2.5cm⁵⁶ in diameter hailstones and not with the 5cm in diameter hailstones that climate change is causing.

Furthermore, hailstorms can shatter panels, but they can also cause no visible damage but hide microscopic cracks⁵⁷ inside solar cells that can reduce panels output and potentially cause hotspots⁵⁸ in panels, further reducing their lifespan. However, the effect of these micro cracks takes several months or years to become apparent, making hailstorms even more dangerous for the health of solar systems.

In addition, the increase in other extreme weather events such as lightning, due to similar reasons as hail, poses a big and often underestimated threat⁵⁹ to large-scale solar farms as they are large metal rich targets. Solar farms can be affected by direct and indirect lightning strikes; even though direct strikes have more severe impacts, though localised, indirect strikes pose a greater risk for the entire system. Indirect strikes⁶⁰ can induce high-voltage surges across the system damaging inverters and controllers. This damage is often not immediately noticeable and can result in the failure of components months later, posing an issue for insurance or warranty coverage⁶¹.

Moreover, the increase in frequency and intensity of tropical cyclones and sea level rise pose major threats to the feasibility of solar farm projects in low-lying areas, such as Southeast Asia and the Gulf of Mexico. Warmer sea surface temperatures and greater atmospheric moisture, caused by climate change, are resulting in stronger tropical cyclones⁶² that can completely destroy solar farms. At same time, sea level rise can result in saltwater intrusion⁶³ accelerating the corrosion of metal components and reducing their lifespan. Tropical cyclones along with sea level rise are a great threat to the construction of coastal or offshore solar farms.

Pollution

Pollution caused by wildfire aerosols and dust storms poses a significant challenge to the performance and maintenance of solar energy systems⁶⁴. Solar farms tend to be in regions with high solar irradiance, where wildfires are more likely to occur. Around 25%

⁵⁶ 2023 Eliot Cadoni (Science Direct) Advanced characterisation of photovoltaics for hail resistance <https://www.sciencedirect.com/science/article/pii/S0167577X23015562>

⁵⁷ 2019 Teule, Thirza The vulnerability of solar panels to hail https://research.vu.nl/ws/portalfiles/portal/99414733/Final_public_report_Vulnerability_of_solar_panels_to_hail_risk.pdf

⁵⁸ August 2020 Mathhar Bdoor (MDPI) A comprehensive evaluation on types of micro-cracks and possible effects on power degradation in photovoltaic solar panels <https://www.mdpi.com/2071-1050/12/16/6416>

⁵⁹ 2025 Cristina Daimiel (Clir Renewables) <https://www.clir.eco/blog/lightning-solar-farms>

⁶⁰ December 2024 Anis Niza Ramani (Research Gate) Impact study on indirect lightning strikes on photovoltaic systems near transmission lines https://www.researchgate.net/publication/386305805_Impact_study_on_indirect_lightning_strikes_on_photovoltaic_systems_near_transmission_lines

⁶¹ March 2024 (Your Energy Answers) Can hail damage my solar panels? Here's what you need to know! <https://www.youtube.com/watch?v=bnxJS-YHHIs>

⁶² (Environmental Defence Fund) How climate change makes hurricanes more destructive <https://www.edf.org/climate/how-climate-change-makes-hurricanes-more-destructive>

⁶³ June 2024 (Smart Energy Gap) How does global warming affect solar energy in the atmosphere? <https://smartenergygap.com/how-global-warming-affect-solar-energy/>

⁶⁴ November 2023 Marinko Stojkov Effects of extreme weather conditions on PV systems <https://www.mdpi.com/2071-1050/15/22/16044>

of solar farms are in regions with 200+ days of fire weather⁶⁵, a set of meteorological conditions where wildfires are more likely to occur and propagate per year.

Climate change will further increase the frequency of wildfires: as hotter global temperatures will result in drier, more flammable vegetation, longer fire seasons and more fire weather conditions. The smoke particles from these wildfires scatter and absorb the incoming sunlight reducing solar irradiance by 10 to 30%⁶⁶, resulting in noticeable output drops even for solar farms hundreds of kilometres away from the wildfire. This was the case of 2020 bush fires in Australia⁶⁷ and this also happens on a yearly basis in California.

The deposition of ash and particulates does not only decrease solar output and deteriorate the surface of the panel, but also results in more solar panel cleaning, resulting in greater maintenance costs⁶⁸. Dust causes the same issue and studies show that solar panels in desert locations can lose over 20% of annual energy output⁶⁹. As climate change intensifies desertification and land degradation, dust storm frequency and severity is expected to increase, significantly reducing efficiency if panels are left uncleaned⁷⁰.

This can be a large problem in the areas that are affected by dust storms such as Middle East, North Africa or Australia, as water tends to be scarce in these areas. The maintenance costs associated with cleaning the panels due to aerosols from wildfires and dust from dust storms can discourage the development of solar farms in desert or semi-arid areas.

Climate variability

Increased climate variability caused by climate change can pose seriously important threats to solar energy systems⁷¹.

⁶⁵ July 2024 (Swiss Re) Catching the sun: Adapting solar power to the challenges of climate change <https://www.preventionweb.net/news/catching-sun-adapting-solar-power-challenges-climate-change>

⁶⁶ June 2023 Mengmeng Cai Final Technical Report: Impact of wildfires on solar generation, reserves, and Energy Prices <https://docs.nrel.gov/docs/fy23osti/86640.pdf>

⁶⁷ February 2024 Ethan Ford (iScience) Quantifying the impact of wildfire smoke on solar photovoltaic generation in Australia <https://www.sciencedirect.com/science/article/pii/S2589004223026883>

⁶⁸ March 2025 Sufyan Yakubu (ScienceDirect) A holistic review of the effects of dust build up on solar photovoltaic panel efficiency <https://www.sciencedirect.com/science/article/pii/S2772940024000353>

⁶⁹ March 2025 Sufyan Yakubu (ScienceDirect) A holistic review of the effects of dust build up on solar photovoltaic panel efficiency <https://www.sciencedirect.com/science/article/pii/S2772940024000353>

⁷⁰ December 2024 Said Zakaria (ResearchGate) Dust impact on solar PV performance: A critical review of optimal cleaning techniques for yield enhancement across varied environmental conditions https://www.researchgate.net/publication/382239228_Dust_impact_on_solar_PV_performance_A_critical_review_of_optimal_cleaning_techniques_for_yield_enhancement_across_varied_environmental_conditions

⁷¹ 2021 Sarah Feron Climate change extremes and photovoltaic power output https://jacksonlab.stanford.edu/sites/g/files/sbiybj20871/files/media/file/feron_et_al_2021_nat_sust.pdf

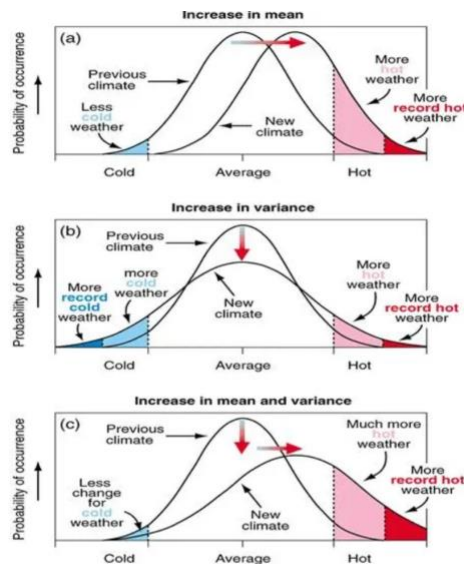


Figure 1 Climate Variability

As global climate systems destabilise, regions are experiencing greater fluctuations between periods of solar abundance and solar droughts and periods of low solar irradiance caused by greater cloud cover, causing unexpected output variability. This is an issue globally, with areas such as Sub-Saharan Africa and Southeast Asia being particularly affected due to shifting monsoon patterns⁷². Furthermore, this can cause solar farms to over or underperform and lower investor confidence due to the uncertainty involved with the site selection process. Most importantly, this output variability can result in energy security concerns in regions that are very dependent on solar energy.

Geographic Risk Mapping

Global outline

Mitiga's climate risk software, EarthScan, can assess the climate risk of a specific asset by only receiving its location, it can then assess its exposure to 6 hazards: flooding, wind risk, heat stress, precipitation risk, drought and wildfire risk. For every hazard, Earth Scan provides a rating from A to F (best to worst), these hazards are then combined to provide a combined physical risk rating with 3 emission scenarios in mind: business as usual, emissions peak in 2040, and Paris Agreement aligned.

We used EarthScan to evaluate 3,400 of the largest global solar PV assets⁷³ (in operation, in construction, in pre-construction or announced) of over 150MW of capacity.

⁷² Yen Yi Loo (ScienceDirect) Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia <https://www.sciencedirect.com/science/article/pii/S167498711400036X>

⁷³ February 2025 (Global Energy Monitor) Global Solar Power Tracker <https://globalenergymonitor.org/projects/global-solar-power-tracker/tracker-map/>

EarthScan came to some key conclusions regarding the exposure of solar PV assets to climate change. Solar assets were on an exceptionally negative rating of 279 (0 highest risk 999 lowest risk) being in the E tier regarding combined physical risk in all emission scenarios. This E rating can be translated to a very high-risk regarding climate change, nevertheless not all hazards are affected by climate change equally. For example, the assets will be at an elevated risk of heat stress with a C rating, which is the main hazard that can severely limit solar assets performance and lifecycle as explained previously.

This hazard already has a significant impact and, as it will only be heightened by climate change, its risk will most likely increase to a D rating by 2050. The feasibility and profitability of solar energy projects globally is therefore at risk.



Figure 3 Global ratings

Furthermore, the heat stress C rating is the same across all categories of projects, announced, in construction or operating; heat stress being the fastest growing climate risk hazard. Despite the B risk for wildfires seeming not to be damaging for solar panels, the nature of the aerosols emitted by wildfires can be a major issue as they are able to travel thousands of kilometers. As a result, aerosols from areas where wildfire risks are considerable can reduce solar irradiance, reducing solar output even at thousands of kilometers away, in areas believed safe. Moreover, wind risk and flood risk are not significant risks for solar assets as a whole but certain coastal areas prone to cyclones can be severely at risk.

Precipitation risk can be a particular threat in areas that are prone to hail events, such as the Hail Alley in the US, causing the destruction of entire solar farms. It is important to underline that a high precipitation risk is not always translated to the presence of hail events as these are specific to certain regions called hail belts. Nevertheless, this precipitation risk does suggest an increase in the presence of storms that could weaken solar farms via direct or indirect lightning. Precipitation risk can be a genuine issue in warm desert areas like the Middle East as warm air holds more moisture when the atmospheric conditions rarely allow for precipitation.

Even though drought does not affect solar panel's efficiency directly, the lack of water to clean panels is a major issue in deserts where dust regularly settles on them. If left uncleaned, dust can lower the efficiency of solar panels by a considerable amount.

In general, solar assets globally are at a significant risk due to climate change, regardless of the completion of the Paris Agreement. As seen in the image above hazards conserve a similar rating independent of the 3 scenarios at least until 2050. The more we expand the timeframe the greater the difference in climate risk scores between the 3 scenarios. Peak-emissions in 2040 and Paris-aligned have a climate risk score of E by 2100 while business as usual experiments a lower F score. In general, climate hazards will continue to increase in severity.

Under a Business as usual scenario, the Combined physical risk will on average increase. This represents a decline in rating over your assets from E in 1970 to F in 2100. The specific risk factor changing most over time is heat stress.

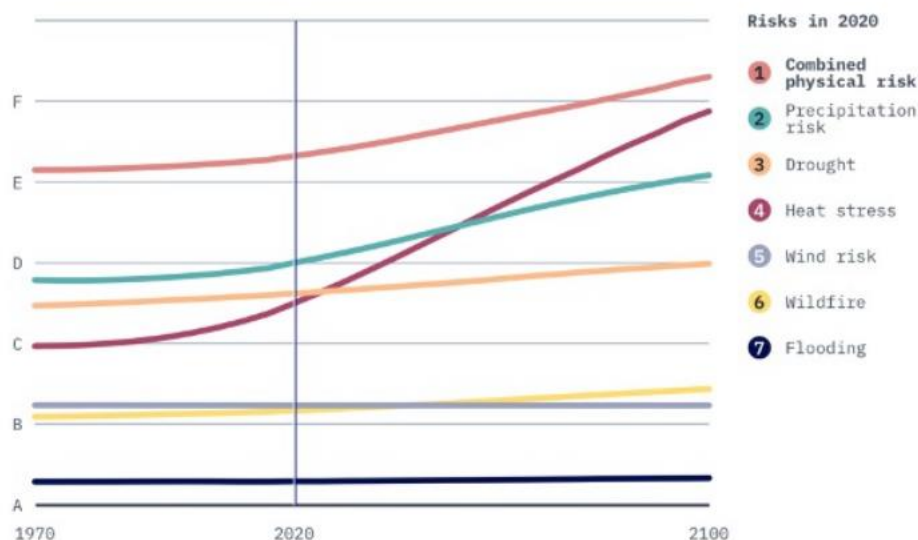


Figure 4 Global ratings graph

Europe

In the case of Europe, it is slightly less affected by climate change as it has a D rating for overall climate risk in 2/3 of the scenarios.

Flooding and wind risk are barely a risk except in coastal areas where the land is more exposed. Nevertheless, the heat stress is a particular issue in Southern Europe where most of the solar farms are concentrated.

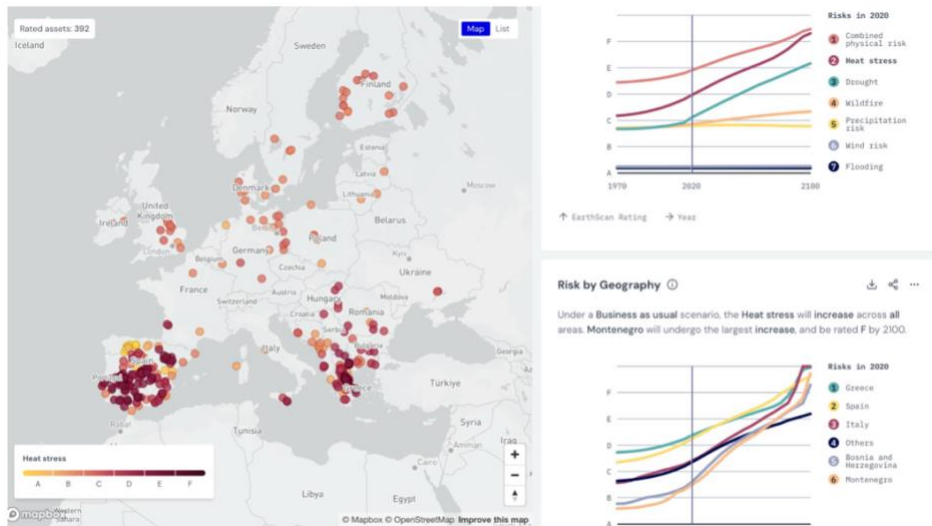


Figure 5 Europe ratings graphs

This is the case in the South of Spain where most solar farms are located and most of them have an E rating due to the frequent heat waves and high average temperatures experienced which will also continue to rise in the region. Despite drought having a C rating and complicating the access of water for the cleaning of solar panels, it is still not a significant issue due to the absence of deserts in Europe.

The settling of dust on these panels from dust or sandstorms is currently not a problem but with increasing desertification rates it could be. This heat stress and drought are also responsible for the higher wildfire risk in Spanish solar farms: while many have an A rating against wildfires, many others have an exceptionally low F rating. Spain's overall rating of E against climate risk can jeopardize its future as one of Europe's largest solar powers despite its immense solar potential. This is also the case with Greece as it suffers from the same climate hazards and is also expanding rapidly its solar capacity.

Heat stress is the major climate hazard affecting solar installations in Europe, even the more northern areas like Finland have a C rating regarding heat stress. Moreover, heat stress will be the fastest growing hazard, and it will be a major issue in countries such as Montenegro which currently does not face this problem as it has a B rating and could obtain an F rating by 2100 if business stays as usual regarding emissions. The solar assets in the pre-construction phase are at a slightly lower level at a border line E rating but with a similar numerical value to the operating assets.

Precipitation risk is not as worrying as there are close to none solar assets around Europe's hail belt (South and Western Germany, Eastern France, and Northern Italy) and lightning is not as dangerous especially when precipitation risk is at a B rating. In general, the solar assets in Europe are at a lower risk than other areas but heat stress continues to be the main hazard and unfortunately one of the most damaging ones for solar panel performance.

Focusing only on the Iberian Peninsula (Spain and Portugal) where almost half of Europe's solar assets above 150 MW are located, we can notice how vulnerable this

region is to climate change with an E rating, especially the Southern Region. In this case, the risk rating is similar across different capacity classes with assets over 500 MW being especially vulnerable to wildfires with a D rating instead of a C rating. Fortunately, the announced and in construction solar farms have a more favorable E rating compared to the current operating solar farms in the peninsula that have an F rating due to their presence in arid, warm and wildfire prone regions, like Andalusia.

Under a Business as usual scenario, the Combined physical risk will on average increase. This represents a decline in rating over your assets from E in 1970 to F in 2100. The specific risk factor changing most over time is heat stress.

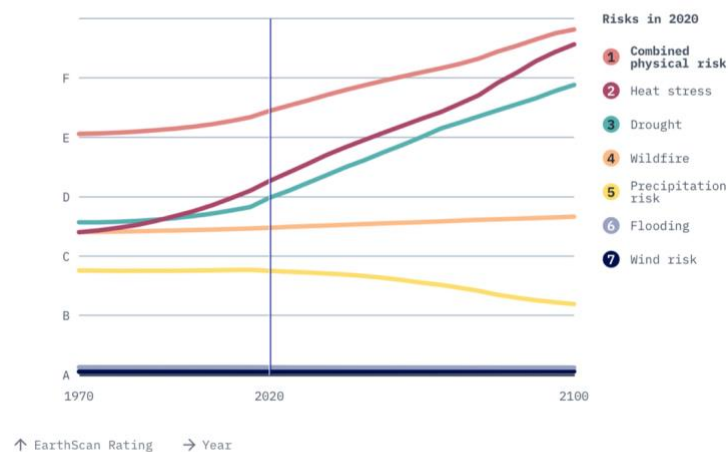


Figure 6 Iberian Peninsula ratings graph

At least, precipitation risk will decrease across the peninsula making storms and the lightning derived from them less of an issue for solar assets. On the other hand, the increase in drought conditions will result in increased cleaning costs as solar panels require cleaning.

37% of solar assets in the Iberian Peninsula are under an E risk rating for heat stress and only the assets in Northwestern Spain are less vulnerable. This poses a major challenge for the EU's energy transition towards renewable energies as solar energy is at notable risk.

Greece, a country with close to 25% of Europe's solar assets above 150MW also suffers the same issue as the Iberian Peninsula but with an even more concerning figure on heat stress.

Risk Distribution ⓘ



In 2020, out of the selected 88 assets, the most common risk rating will be D for Heat stress under a Business as usual scenario. At this time, 30 (34.1%) assets will likely be rated E.

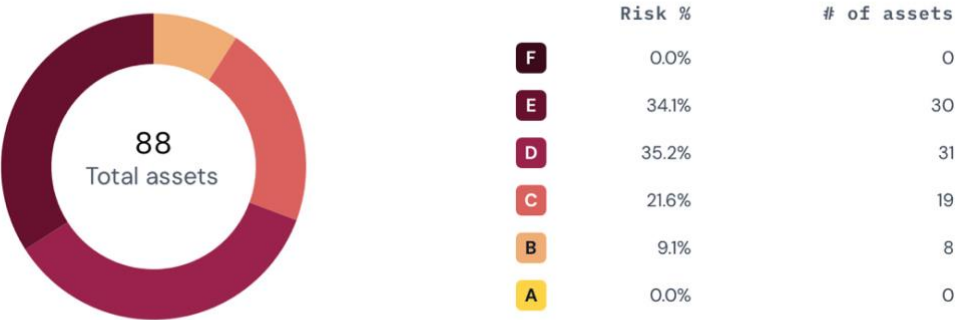


Figure 7 Greece ratings pie chart

Heat stress is becoming a bigger concern as it is even affecting the Nordic countries of Finland and Sweden, which are known for their cold weather. Their current C heat stress rating could continue to rise to even higher levels, something unheard of for such northern regions.

Heat stress under a Emissions peak in 2040 scenario, will on average increase relative to 1970 risk levels over the next century. By 2100 average risk levels across your assets will be rated D.

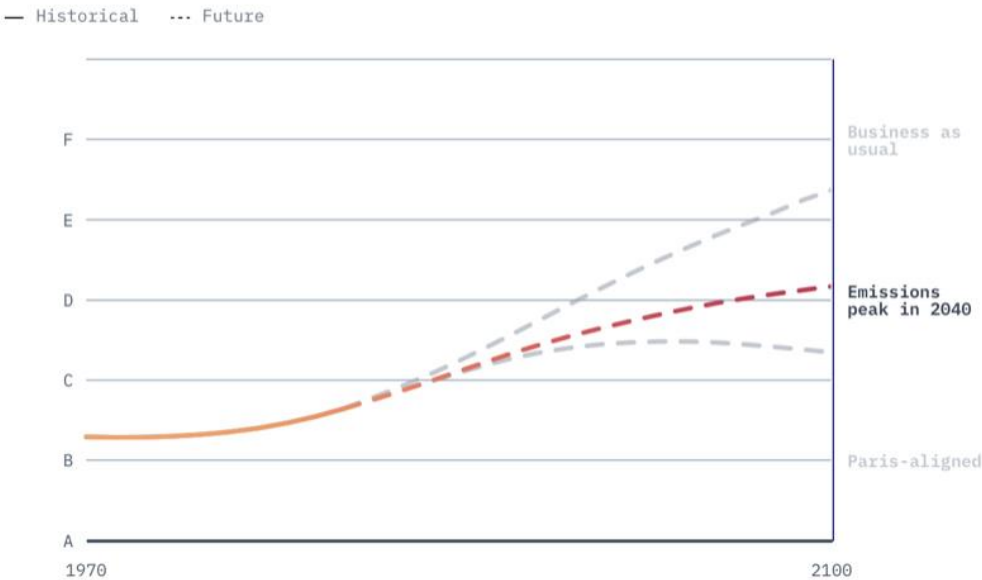


Figure 8 Nordic countries heat stress graph

In other hazards there are clear outliers, Montenegro being the country with the greatest precipitation risk by far.

Under a **Business as usual** scenario, the **Precipitation risk** will **increase** across **some** areas. Finland will undergo the largest **increase**, and be rated **C** by 2100.

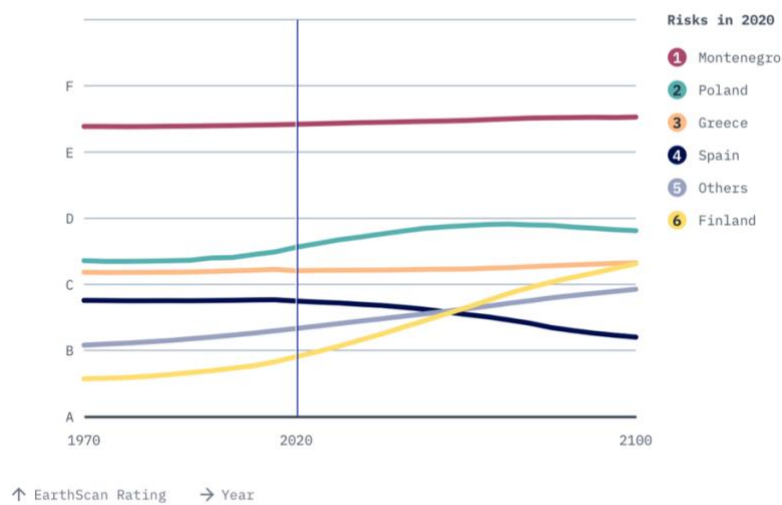


Figure 9 Precipitation risk by countries Europe graph

In general, while Europe appears comparatively less exposed, the speed at which heat stress and drought are intensifying, particularly in the south, is genuinely concerning. Without smarter asset siting and stronger resilience measures some of Europe's largest solar farms could face rapid performance degradation and decreased output.

The Americas

The Americas are greatly affected by climate change as their solar assets have an E rating; however, this score takes drought into account, which is not a significant risk for solar assets, many solar locations have an F rating due to their location amongst arid areas. As these arid areas lack rainfall the cleaning of solar panels can be difficult if dust from sandstorms settles on them, however not all deserts in the Americas are formed of solely sand so they are not affected by drought equally.



Figure 10 Americas ratings

Flooding still conserves a low rating as solar farms are not built on low ground in the Americas. Compared to Europe, the Americas are more affected by wind (C rating vs A rating) due to the existence of many solar farms around the American coastline surrounding the Gulf of Mexico, an area that is very exposed to hurricanes and will be more exposed with rising sea temperatures, resulting in a high precipitation risk score too.

As a result, the area surrounding the Gulf of Mexico is very exposed to climate change due to its high heat stress and high precipitation and wind risk due to hurricanes. This situation can be further complicated due to the wildfire risk that these areas can be subject to.

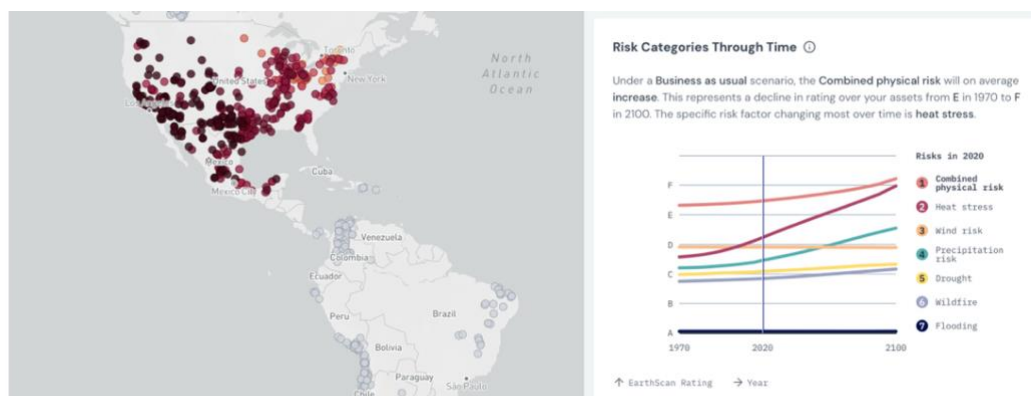


Figure 11 USA ratings graph

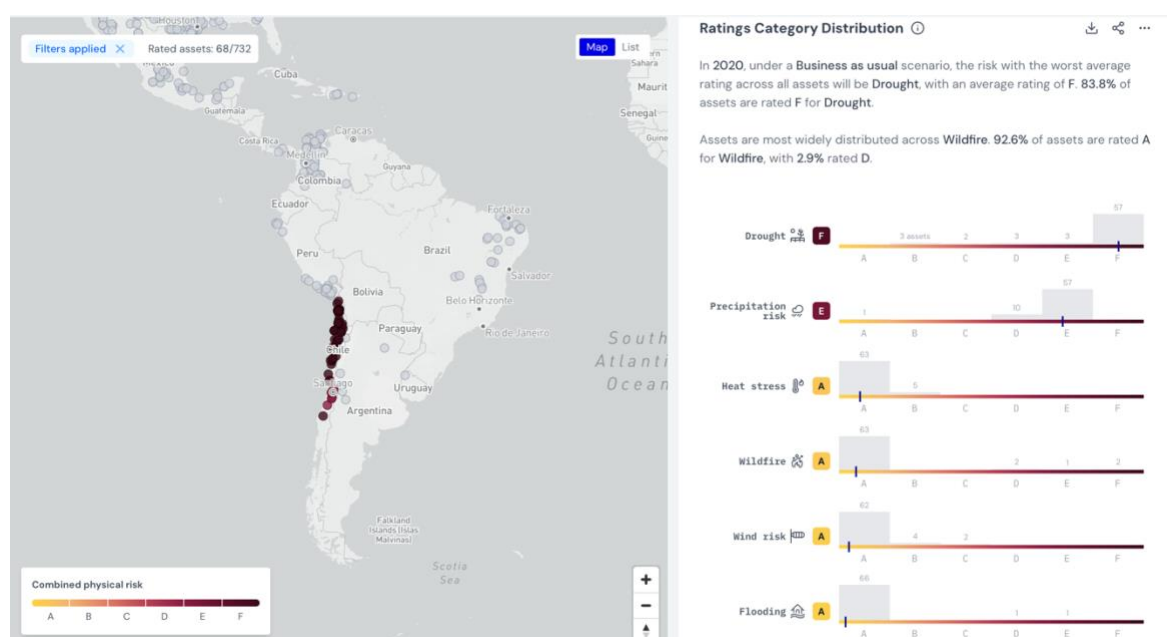
As a result, 1/3 of solar assets in the US have a risk rating of F, this occurs mostly across the southern border, central areas and along the Gulf of Mexico as appreciated on the map above. This situation is further complicated in the state of Texas and central US located in the hail valley, where the rainfall risk can be directly translated to more frequent hailstorms which could destroy the panels.

Nevertheless, different areas experience low ratings mostly due to drought, which is not always directly translated to wildfire risk, this is the case of Chile and Brazil. If we compare heat stress between locations, we can clearly see that locations between the American and Mexican border are the most affected by climate change as a whole. Nonetheless, the 2 largest solar assets found in the Americas, that are within the 5,000–10,000 MW range, are in Brazil and have an overall rating of F. The 4 largest assets in the US (found in the 1,000–2,000 MW category) have a combined physical risk rating of D, close to E. Regardless of the status of the solar asset, they all have a risk rating of E which poses the question of where sites should be located.

Focusing on the Western coast region in South America where Chile contains close to 10% of the solar assets above 150 MW, we can notice how drought is a severe hazard for solar assets. This is because the majority of Chile's solar assets are found in the Atacama Desert, along the western foothills of the Andes mountains, an area of high

altitude and exceptionally low precipitation. This drought can complicate the assets cleaning and maintenance, as dust can accumulate on the panels' surfaces resulting in higher operating costs related to their cleaning.

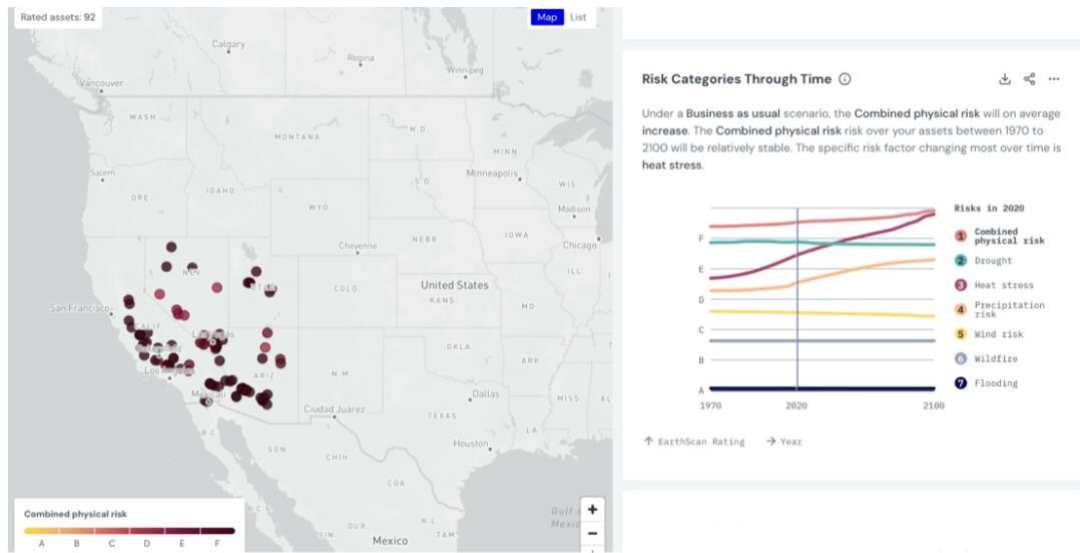
As these are cold deserts its impact is not linked to elevated temperatures, so this risk is lower than the one present in the deserts in the Southwest of US, the Sonoran and Mojave. This area is at a high precipitation risk as, despite being scarce, rainfall arrives in large amounts in very short periods of times causing flash floods. The combination of rare rainfall and extreme storm intensity means that most solar installations are not prepared for water resilience, exposing them more in the case of these extreme storm events.



This trend is repeated across all capacity thresholds. In general, Chile has great solar potential but without clear strategies to face the drought-driven maintenance challenges and flash flood hazards, the proliferation of solar energy in the country could be at risk.

Focusing on the arid states of California, Utah, Nevada and Arizona, where the Mohave, Sonoran and Great Basin Deserts are found, we find an area with a high solar farm concentration, more than 10% of solar farms in the Americas, despite their F climate risk rating. This area has similar risks than the Atacama Desert but as it is comprised of hot deserts, heat stress is an added risk that seriously affects asset performance. Furthermore, this area is known for frequent dust and sandstorms that added to the intense drought in the area, make panel cleaning a labour intensive and expensive operation.

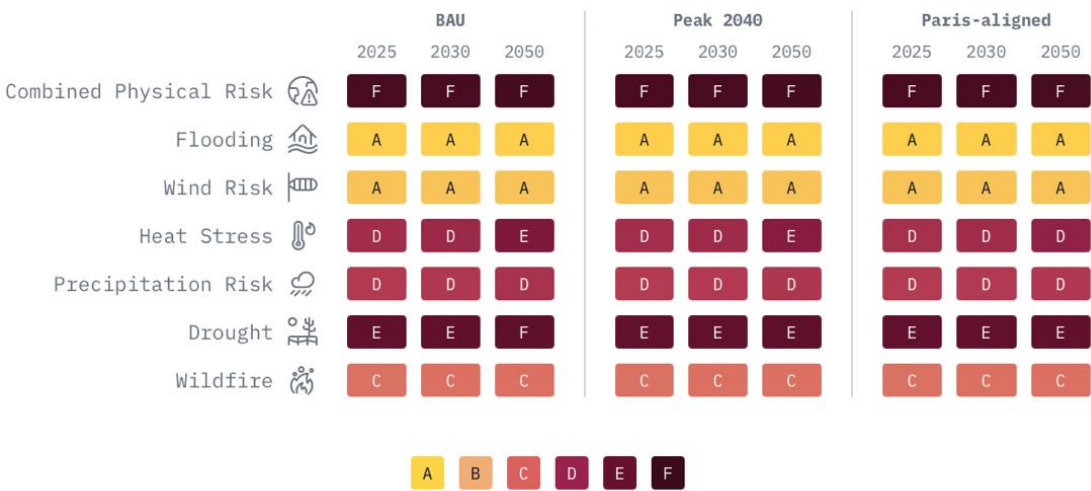
Similarly to the Atacama region, this area experiences occasional extreme rainfall events that lead to flash flooding in an area severely underprepared for these events. The A rating for floods makes reference to a low persistent or basin-scale flooding not to the risk of flash floods which is included in the precipitation risk.



In general, this region exemplifies the paradox of solar rich deserts as, despite having very good conditions for solar energy, they are also vulnerable to heat, dust and water-related shortages. Therefore, without climate-resilient planning, this area of Southwest US will not be able to capitalise on its immense solar potential.

Africa

In Africa, solar assets have the lowest overall score of F, primarily due to the high levels of drought present in the areas of greatest solar potential in North Africa, where the majority of solar farms are located amongst the desert or very arid areas.



Furthermore, the lack of rainfall can be a problem in the Sahara Desert, where dust settles on solar panels, and the lack of water complicates the cleaning of these panels resulting in great efficiency losses of up to 40% if left uncleaned during weeks. If this dust is left uncleaned, hotspots can form, surface degradation can occur, which, coupled with higher operating temperatures will lead to a decreased output. Although, this drought does not directly concern solar panels, these deserts are extremely hot causing heat stress to be the major concern for solar farms leading to efficiency losses.

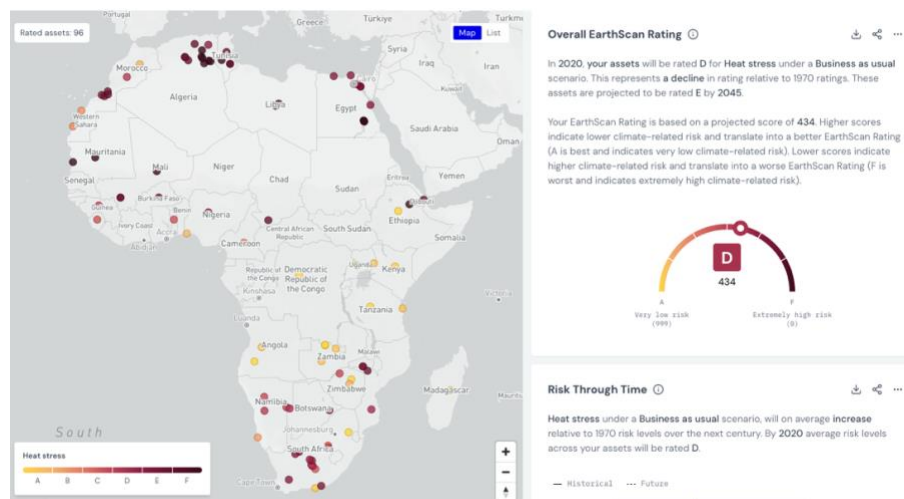


Figure 15 Africa rating

Although heat stress is not a source of concern for all countries in Africa, it is the most impactful in the areas with the greatest concentration of solar farms like Northern Africa or South Africa. The 3 largest solar farms in the continent with a capacity of over 10,000 MW have a risk rating of E regarding heat stress and the solar plants between 5,000–10,000 MW have an equally concerning heat stress of D rating and almost E rating. Heat stress risk will continue to rise in the continent even in areas that are not under a significant risk nowadays like Cameroon.

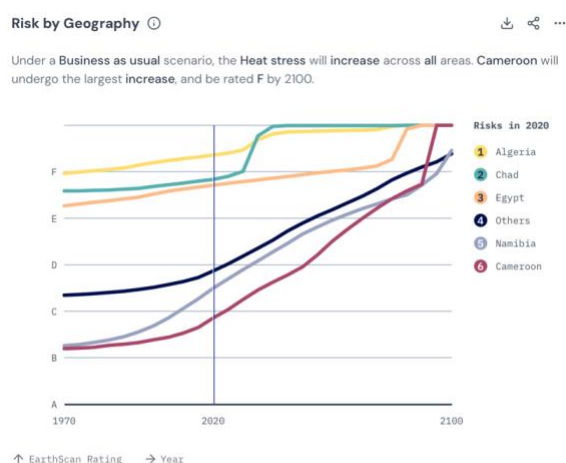


Figure 16 Heat stress by countries Africa graph

Wildfire risk is also a major source of concern for areas of Southern Africa and under the correct atmospheric conditions these aerosols could lower efficiency of solar farms even in Northern Africa. These areas of Southern Africa are also particularly vulnerable to precipitation risk as they are found amongst a hail belt, where this precipitation risk can be translated into an increased hail risk which could, in many instances, completely destroy solar farms.

On the other hand, wind and flooding risk is non-existent except in a few coastal cases. The 3 largest solar plants in Africa with a capacity of over 10,000 MW have a combined physical risk score of C with drought, heat stress, and precipitation risk being their biggest threat.

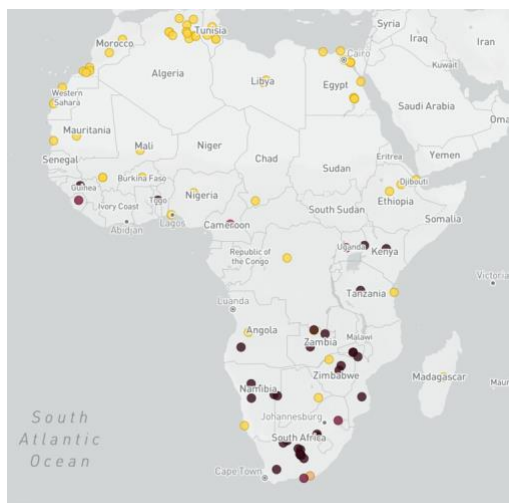


Figure 17 Africa wildfire risk map

Focusing on Northern Africa, a region dominated by very arid and hot environments, over 85% of assets are rated F for drought. Some of the world's most ambitious solar projects are based in this area such as Libya, home to a solar power plant that will have around 25,000 MW in capacity, enough to power millions of homes. In addition, these assets have some of the world's worst combined physical risk scores with an F rating of 49/999 as most assets are seriously threatened by drought, heat stress and precipitation risk.

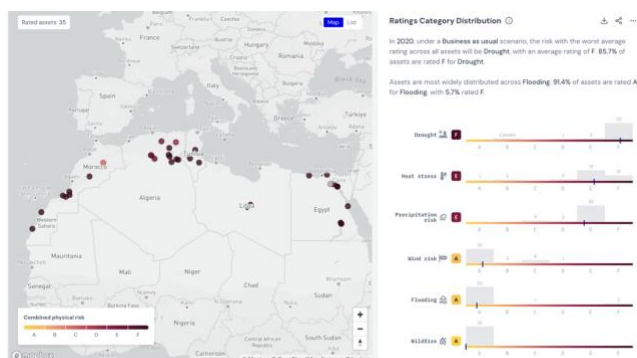


Figure 18 Northern Africa risk distribution

As a result, trees have an extremely tough time growing in the region, so wildfire risk is very low along with wind and flooding risk. Precipitation risk (E rated) is often

underestimated due to the arid nature of the region, but it is responsible for short and sudden storm bursts that lead to flash flooding. As barren ground cannot absorb much water this can result in the destruction of solar assets. This precipitation risk occurs as warmer air holds more moisture and, in the rare case that atmospheric conditions allow for precipitation, this event will be more intense and dangerous.

Drought and heat stress continue to be the major climate hazards. In particular heat stress can pose significant decreases in efficiency of solar panels especially across higher temperatures where the decrease in efficiency per degree starts to adopt an exponential behaviour. The temperatures in this region can reach up to 50°C and, as panels are 20-25 degrees warmer, efficiency can drop by up to 25% and solar panels will suffer extensive degradation.

Additionally, drought poses an operational burden as there is a lack of water to clean panels that are often affected by dust and sandstorms due to their presence surrounding the Sahara Desert. If left uncleaned the lifespan and efficiency of these panels will be seriously at risk. In conclusion, while Northern Africa holds immense solar potential, its solar future will depend on how effectively developers and governments address the operational challenges.



Figure 19 Northern Africa heat stress and drought risk graphs

Focusing on Southern Africa, this area is severely affected by climate change in many different ways to Northern Africa. While average temperatures are lower, the region is still affected by drought and has added wildfire risk (75% of solar assets are rated F in this category). High wildfire risk is due to the presence of grassland and vegetation that is able to grow as it is not under such severe conditions that are present in the North. While heat stress is lower, it still causes notable efficiency losses that can be further aggravated by aerosols released by wildfires.

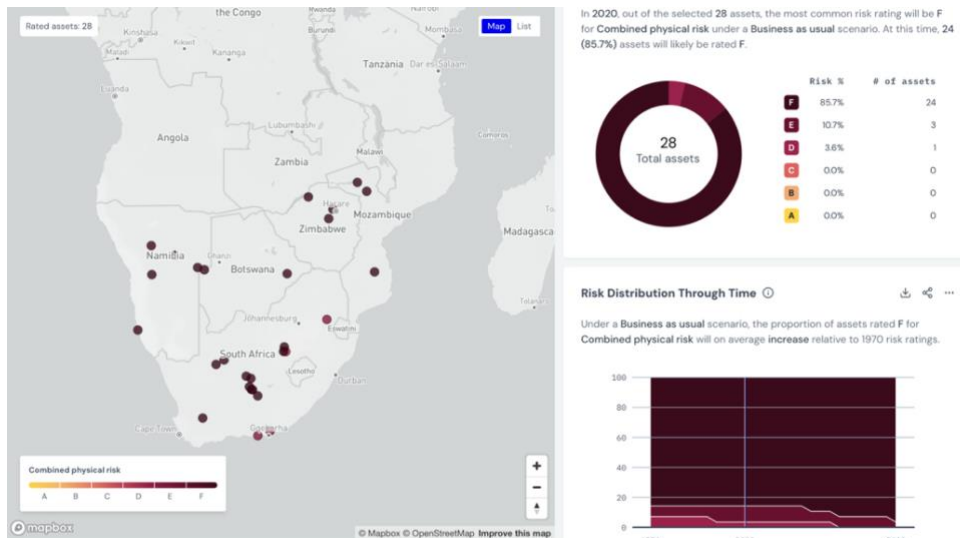


Figure 20 Southern Africa pie chart ratings

In addition, South Africa has a hail belt, an area prone to hail events, in their central and eastern regions that turns this relatively low precipitation risk rating of C into a much serious rating. Despite not being as lightning prone as the more northern Sub-Saharan countries, Southern Africa still receives a greater than average amount of lightning that, whether direct or indirect, can damage solar farms to a similar degree than big hail events.

Despite flood risk being very insignificant, flash floods can still occur and can have the potential to cause great harm in the most barren areas of the region. South Africa, as the largest solar power producer in Africa, along with the rest of countries in the region must adapt to rising climate threats by integrating resilient infrastructure and long-term risk planning.

Asia

Asia is one of the most vulnerable continents regarding climate change as has an overall E rating. Its major climate hazards are precipitation risk, drought and heat



Figure 21 Asia ratings

stress. Heat stress is the main cause of concern for solar panels across the Middle East and the West of India where they have a rating of F regarding heat stress and drought.

As a result, solar panels efficiency and lifespan are reduced because of excessive heat on them and lack of water to clean panels that can suffer permanent damage from dust storms in the Middle East. Despite being very arid, these areas are at a very high E risk rating regarding precipitation, as rain is rare but intense in these regions. Soil and infrastructure cannot handle precipitation resulting in flash floods that can destroy entire solar installations.

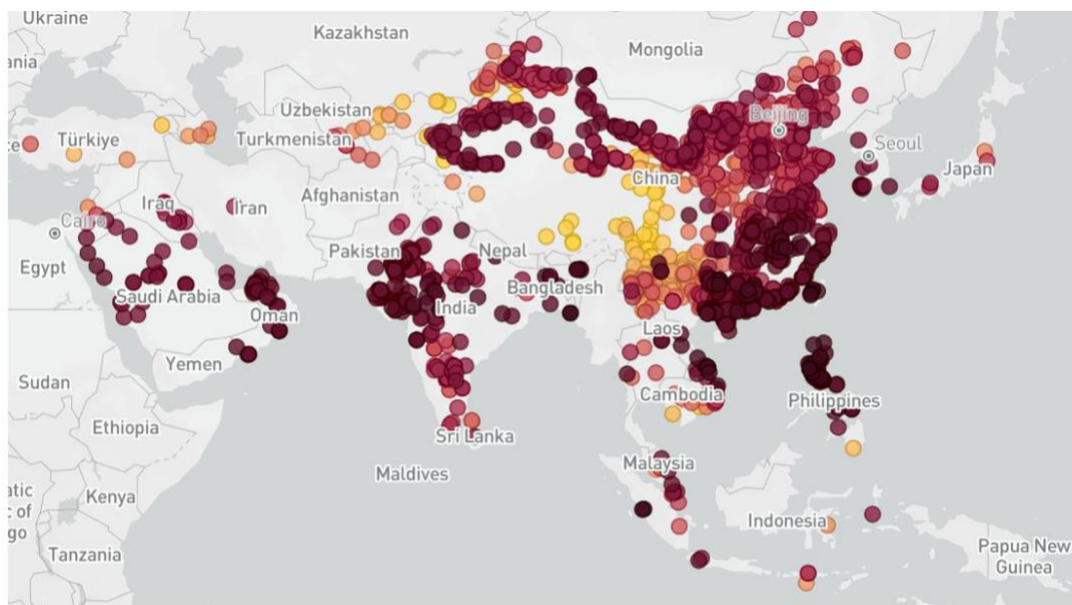


Figure 22 Asia ratings map

Other areas have a high precipitation risk due to their location around the typhoon prone areas in the Philippine and South China Sea. These typhoons seriously jeopardise the safety of coastal solar farms that can be torn apart or devastated by floods derived from these typhoons. In southern parts of China this increased precipitation risk results in hail that can destroy entire solar panel installations.

These areas are also very vulnerable to wind that could also cause the destruction of these solar farms. Wind has a considerable risk rating in the areas that are commonly hit by typhoons across the Philippine Sea. The wildfire risk in Asia is lower compared to other continents and is mostly concentrated in Northeast China.

China

China, the world's solar superpower, in terms of solar capacity and solar panel installation, is greatly exposed to climate change with a D, borderline E, rating for combined physical risk.

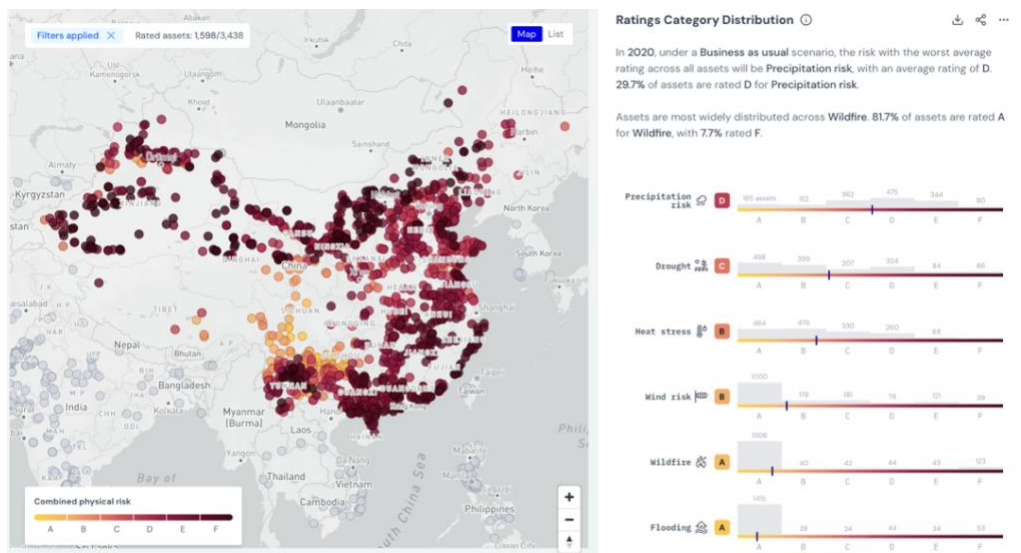


Figure 23 China ratings distribution

China is home to close to half of the world's largest solar farms (1,000 MW+) and close to half of the global solar farms with a capacity over 150MW. China has a great solar potential and has areas with very high solar farm density, particularly in the East, where climate risk is nevertheless high. Due to China's substantial number of solar plants and China's enormous size, solar plants experience all types of climate hazards, all categories except heat stress have assets F rated, but not simultaneously.

For example, the Northeast of China is particularly prone to wildfires that could affect other solar plants thousands of kilometres away due to the aerosols, a considerable problem in China, due to human derived pollution.

The Southeast of China is vulnerable to typhoons due to its location around the Philippine and South China Sea. This region experiences an increased flooding, wind and precipitation risk that can be particularly damaging as this area is found amongst a hail belt.

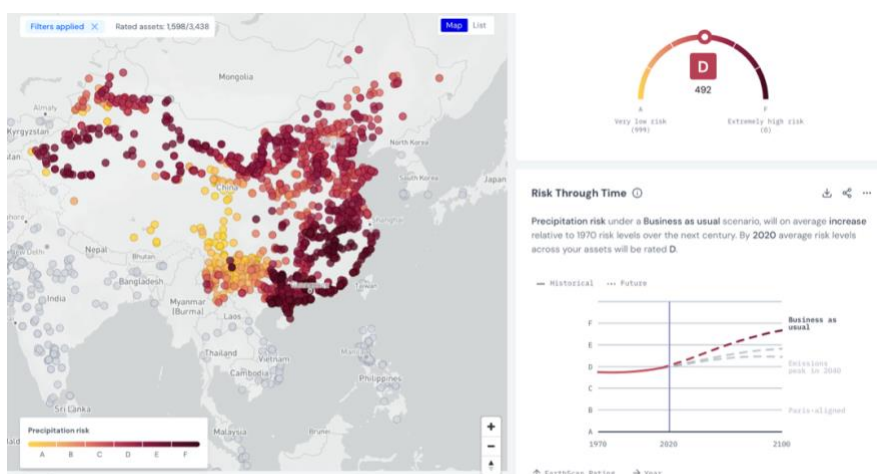


Figure 24 China precipitation risk map

At least, the Southeast of China is not vulnerable to drought as it does not contain deserts unlike the North and West of China with the presence of the Gobi and Takla Makan Deserts. Due to their nature, maintenance costs in these desert areas are higher as water for cleaning solar panels from dust and sand is scarcer; however, these deserts are considered cold so heat stress is at a lower risk than in other deserts such as the ones found in the Middle East.

Heat stress is currently not a serious issue with a B rating but, along with precipitation risk, ratings will rise at extreme rates. Heat stress will become a major issue which China does not currently face, heat stress could rise from a B rating to an E rating by 2100 if emissions stay at current levels. This is even visible nowadays as the 3 largest solar farms in China with a capacity between 5,000–10,000 MW have a F rating and are particularly prone to drought and heat stress. To conclude, while China leads the world in solar capacity, it must adopt climate-resilient planning to safeguard its solar future.

Under a Business as usual scenario, the Combined physical risk will on average increase. This represents a decline in rating over your assets from D in 1970 to F in 2100. The specific risk factor changing most over time is heat stress.

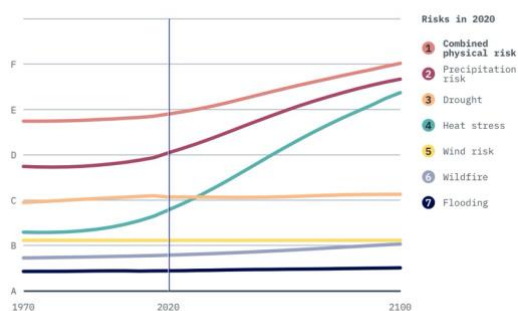


Figure 25 China ratings graph

Middle East

Focusing on the Middle East, this area has a very low climate risk score with an F rating and a 2/999 score, mainly driven by drought (a large part of it is a desert), heat stress and precipitation risk coming from the occasional intense events. All the 69 assets have an F rating, while they have a minimum risk for wind, flooding and wildfire risk. Heat stress, with an F rating poses the biggest threat to solar efficiency and lifespan, while drought with an F rating substantially raises operating costs associated with the cleaning of panels in an area where dust and sandstorms are common.

Despite being an arid area, precipitation risk is high at an E rating, due to the existence of rare but intense storm bursts that the impermeable desert soil cannot absorb and does not have the infrastructure to manage. This leads to flash floods that can destroy solar assets and their associated structures. Combined, these factors make the Middle East's solar assets some of the most climate-exposed in the world and demand climate resilience planning to allow these nations to take full advantage of their immense solar potential.

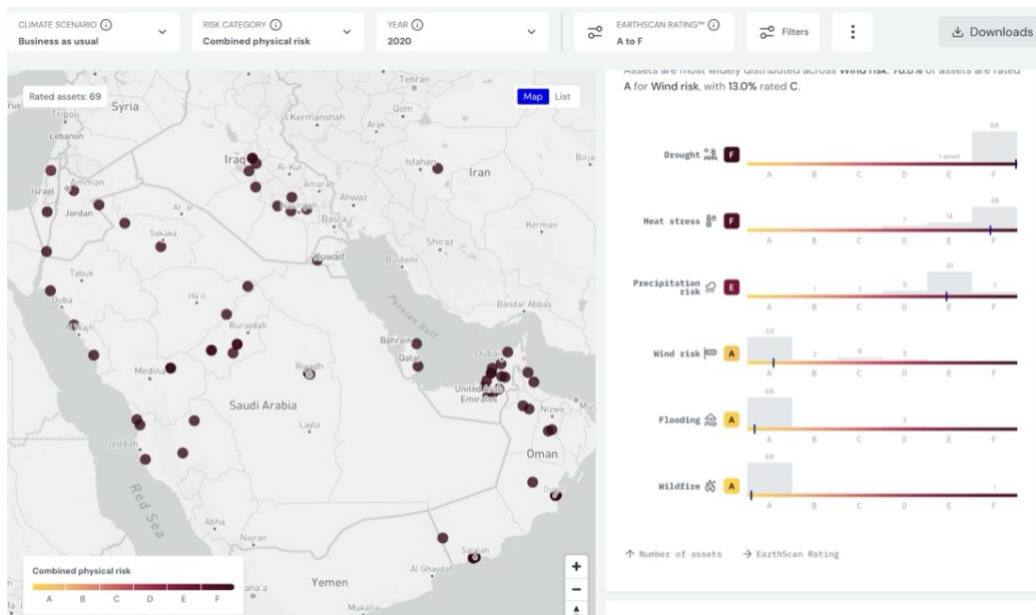


Figure 26 Middle East ratings distribution

India

India is the third largest producer of solar energy worldwide behind China and the US with 20 solar plants of over 1,000 MW in capacity and an immense solar potential particularly amongst the western regions. Nevertheless, it follows the same fate as the Middle East as it also has a low F combined physical rating and its major climate hazards drought, heat stress and precipitation risk have the same ratings.

Compared to the nations in the Middle East, India suffers from a greater wind risk as India is regularly impacted by cyclones, but these primarily affect the East of India in the Bay of Bengal. This region does not have many solar assets so the wind risk rating stays at an acceptable B.

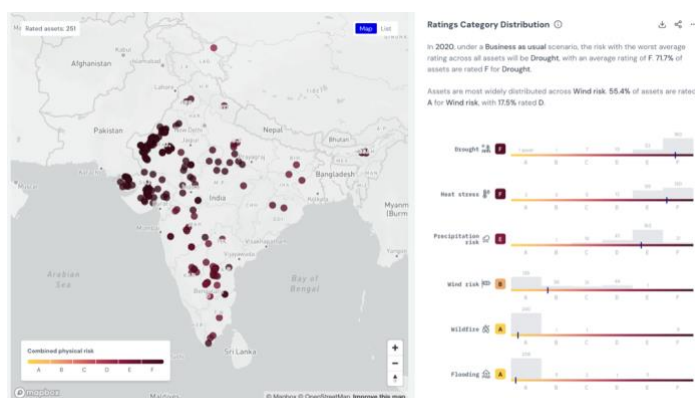


Figure 27 India ratings distribution

Furthermore, India's third major hazard, precipitation risk, is driven by India's volatile monsoon system, which brings intense, seasonal rainfall. This monsoon system is responsible for flash floods as heavy rains fall over an arid land that has not received rain throughout the rest of the year and, in turn, cannot absorb rainfall. This monsoon

rain can not only damage solar panels themselves, but they can seriously damage all the electrical infrastructure surrounding solar panels, inverters and much more.

This precipitation risk can be further aggravated in areas of North and East India that are located in a hail belt, where precipitation risk is related to hail that is the most threatening risk of all for solar panels. Adding to hail related maintenance costs, drought is also a major operational cost driver for solar installations, in the regions of Gujarat and Rajasthan. In general, to fully **take advantage of its immense solar potential**, India must incorporate climate-resilience into its project planning for solar assets.

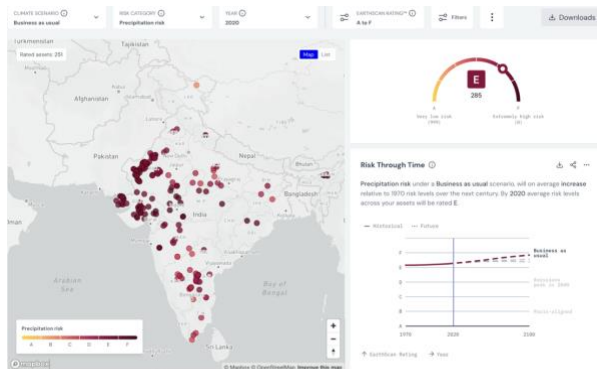


Figure 28 India precipitation risk map

Oceania

In Oceania, the rating is a low E with wildfire, heat stress and precipitation risk being the 3 main climate hazards. Only Australia and New Zealand have solar panel installations over 150 MW, so they are the only 2 oceanic nations represented.

		BAU			Peak 2040			Paris-aligned		
		2025	2030	2050	2025	2030	2050	2025	2030	2050
Combined Physical Risk	🌪️	E	E	E	E	E	E	E	E	E
Flooding	🌊	A	A	A	A	A	A	A	A	A
Wind Risk	💨	A	A	A	A	A	A	A	A	A
Heat Stress	🔥	D	D	D	D	D	D	D	D	D
Precipitation Risk	☁️	D	D	D	D	D	D	D	D	D
Drought	🌵	C	C	C	C	C	C	C	C	C
Wildfire	🔥	D	D	D	D	D	D	D	D	D

Figure 29 Oceania ratings

New Zealand has a combined physical risk of B with precipitation being its only climate hazard below the A tier. New Zealand is in an area prone to hailstorms, in consequence, solar plants are more at risk than we think as hail is the main cause of solar panels being destroyed.

Australia, the country with greatest solar generation per capita is at a substantial risk with a rating of a low E for combined physical risk. Similarly to New Zealand, certain areas of Eastern Australia are particularly prone to hailstorms, in these areas the D

risk for precipitation risk is an even greater threat. This hail prone area matches Australia's region that is most prone to suffering typhoons, making solar panels vulnerable in several ways across the Eastern coast. These typhoons do not increase the flood risk of assets in the area as they are not too coastal or are on higher ground; the same occurs with wind risk although this risk increases in Northeastern Australia and coast areas in Western Australia.

Furthermore, Eastern Australia has the greatest concentration of solar farms and suffers from intense heat stress. Fortunately, the new solar farms in Australia will be less exposed to climate risk as the currently operating solar farms have an F for combined physical risk and are especially vulnerable to wildfires with an F rating.

Assets are most widely distributed across Wildfire. 49.1% of assets are rated F for Wildfire, with 23.6% rated A.



Figure 30 Oceania ratings distribution

The world's future largest solar plant, Western Green Energy Hub, is found in Australia.

With 35,000 MW capacity, it can power over 10 million homes, and has a climate risk rating of F, primarily due to its location in an area prone to wildfires and high heat stress.

		BAU			Peak 2040			Paris-aligned		
		2025	2030	2050	2025	2030	2050	2025	2030	2050
Combined Physical Risk		F	F	F	F	F	F	F	F	F
Flooding		A	A	A	A	A	A	A	A	A
Wind Risk		A	A	A	A	A	A	A	A	A
Heat Stress		E	E	E	E	E	E	E	E	E
Precipitation Risk		E	E	E	E	E	E	E	E	E
Drought		D	D	D	D	D	D	D	D	D
Wildfire		F	F	F	F	F	F	F	F	F

Figure 31 Australia western green energy hub ratings

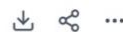
Wildfires are a risk all across Australia and not in New Zealand but could still affect both countries due to the nature of aerosols if conditions are right. This plant is also

at a substantial risk due to precipitation as it is in an arid area that could be at a serious risk of flash flooding when rare storm bursts occur in the region. To conclude, while Oceania is a continent of great solar potential, especially Australia, the region's growing climatic threats must be met by climate-resilient planning to protect long-term solar output.

Key Takeaways

This white paper proves that climate risk poses a major threat to solar energy worldwide as only 1% of solar assets have an A rating regarding combined physical risk.

Risk Distribution ⓘ



In 2020, out of the selected 3,438 assets, the most common risk rating will be F for Combined physical risk under a Business as usual scenario. At this time, 1,256 (36.5%) assets will likely be rated F.

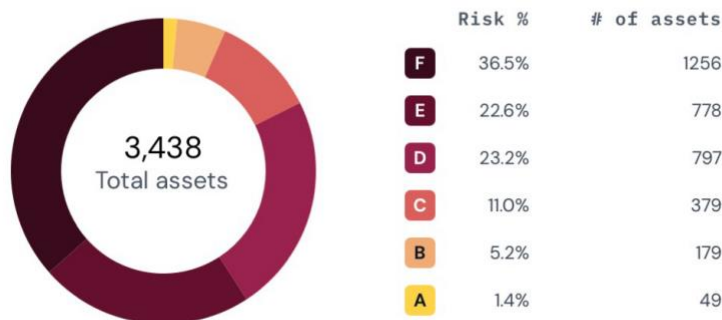


Figure 32 Global pie chart ratings

Heat stress is the fastest growing climate hazard and poses a major threat by reducing efficiency and lifespan of solar assets.

Drought, while not being a direct risk, increases operational costs associated with the cleaning of the panels, especially amongst desert regions.

Precipitation risk is an often-underestimated risk as it has the potential to cause great harm via flash floods that can occur in desert areas, where a considerable proportion of solar assets are found, or via deadly hail events in specific regions.

Hail is the most direct physical hazard to solar farms and its presence in certain areas could greatly discourage investment in solar energy.

Regardless of location all solar assets are exposed to climate change as aerosols from wildfires can travel thousands of kilometers and reduce irradiance. All these hazards are currently jeopardizing the future of solar energy by threatening its performance, reliability and financial viability, making climate resilience no longer optional, but essential for long-term operational success.

Solutions

Climate hazards endangering solar panels can be addressed with both physical and strategic solutions.

Physical solutions

To address hail risk: standard solar panels are only tested for hail stones smaller than 25mm in diameter, too small⁷⁴ compared to hail stone size nowadays in hail prone areas. These panels must be replaced with panels with a greater glass thickness that can withstand the impacts of larger hailstones⁷⁵. While standard panels have a tempered glass thickness of 3.2mm, solar panels in hail prone areas must have a tempered glass thickness of at least 4mm or even 5mm. Studies show that panels with 4mm tempered glass can survive 55mm hail with less than a 2% performance loss⁷⁶.

Solar asset owners must make sure that the panels meet the pertinent hail testing regulations against larger hailstones. Changing tilt angle⁷⁷ and deploying a net to reduce impact velocity are other more labour intense options.

To address heat stress: panels with lower temperature coefficients (lose less efficiency per degree at high temperatures) such as monocrystalline panels⁷⁸, improve natural ventilation around systems and use heat-tolerant electrical components.

To address flooding: panels should be mounted on raised platforms and against wind risk panels should be placed in robust racking systems that are anchored to the ground with deep footings.

Moreover, to protect solar assets against lightning risk⁷⁹, systems must include surge protection devices, grounding, lightning rods, along with proper isolation of sensitive equipment.

Strategic solutions

⁷⁴ August 2024 Aiko sets the new standard in hail resistance for solar panels <https://aikosolar.com/au/aiko-sets-the-new-standard-in-hail-resistance-for-solar-panels/>

⁷⁵ September 2023 (Ceramic Tech) Protecting solar panels from hail—the thicker the glass, the better <https://ceramics.org/ceramic-tech-today/protecting-solar-panels-from-hail-the-thicker-the-glass-the-better/>

⁷⁶ September 2023 (Ceramic Tech) Protecting solar panels from hail—the thicker the glass, the better <https://ceramics.org/ceramic-tech-today/protecting-solar-panels-from-hail-the-thicker-the-glass-the-better/>

⁷⁷ August 2024 Yimin Dai (Scientific reports) Experimental study on the influence of turbulence on hail impacts <https://www.nature.com/articles/s41598-024-69234-5>

⁷⁸ (Ossila) Monocrystalline vs Polycrystalline solar panels <https://www.ossila.com/pages/monocrystalline-vs-polycrystalline-solar-panels>

⁷⁹ François D Martzloff Lightning and surge protection for photovoltaic systems <https://www.nist.gov/system/files/documents/pml/div684/Photovoltaic.pdf>

From a strategic perspective, climate risk modelling should be incorporated in the early decision-making process for solar energy projects to guide site selection and investment. Mitiga's EarthScan becomes a strategic tool to facilitate this decision in the solar energy sector. EarthScan provides key insights into site selection, enabling developers to identify and avoid high-risk areas. Furthermore, EarthScan is able to quantify climate hazards to help solar farm owners prioritise adaptation investments.

EarthScan's global scalable coverage with high-resolution asset-level hazard ratings enables climate risk assessments for smarter investment and siting but not limited to the solar energy sector, all sectors should consider climate resilience when making investment decisions. Climate risk spending provides a high return on investment especially in the solar energy sector as it can increase asset performance and lifespan, reduce maintenance and downtime costs and prevent losses from extreme weather events.

Ultimately, integrating climate risk into everyday investment decisions is essential for ensuring long-term sustainability, financial stability and operational resilience.

Case studies

Capital Dynamics, an independent global asset management firm, focusing on private equity and clean energy, worked with Mitiga⁸⁰ by using flood risk maps to mitigate the risk of catastrophic flooding at their solar PV sites in Italy. Due to Earth Scan's insights Capital Dynamics relocated its battery units to lower risk areas, hence protecting their asset value and ensuring long term resilience. By leveraging EarthScan, Capital Dynamics manages over 200 solar assets and actively reduces their exposure to climate risk by using this climate intelligence to make more informed decisions regarding asset protection, site selection and portfolio planning.

Furthermore, this case clearly illustrates that climate adaptation is not only possible but profitable: as using Earth Scan's insights Capital Dynamics has been able to, in most cases, improve operational efficiency, lower operating costs, lower insurance premiums and lower potential revenue losses.

Mitiga has worked with many other companies in the solar industry tackling other related hazards such as heat stress. For example, Mitiga worked with a leading solar energy company to minimize heat-related downtime for their solar assets. By quantifying the likelihood of extreme heat events using EarthScan, Mitiga allowed this corporation to optimise its actions and minimise downtime. Moreover, EarthScan's insights allowed this company to stay ahead of climate-related disruptions maximising long-term profitability and ensuring that solar assets remain productive and resilient in a warming climate.

⁸⁰ January 2025 (Mitiga solutions) How to assess climate risks for your solar assets? EarthScan and Capital Dynamics (Webinar Recording)
<https://www.youtube.com/watch?v=GyBgoleg1sc>

Conclusion

This white paper has explored the renewable energy paradox: while solar energy is key to resolving climate change, it is also increasingly vulnerable to its impacts.

Solar energy is a clear alternative to fossil fuel. Geopolitical instability and shifting policies have played a big role in the growth of solar plants across different markets. As policy makers and the private sector looks at growing the solar energy sector, addressing climate risk must be explored. Climate hazards cause severe solar efficiency reductions. Understanding which hazards are at play will also trigger solutions and ultimately make the solar energy sector more efficient and robust.

Mitiga's EarthScan product has allowed the risk mapping of over 3,400 solar assets with a capacity of over 150 MW. This risk mapping shows clear findings: areas of great solar potential are usually at a greater risk from climate change; heat stress is the fastest growing and the most performance-damaging hazard and every solar asset is exposed to climate change to a certain degree. Fortunately, physical and strategic solutions are available to reduce vulnerability, from thicker glass panels in hail prone regions to heat-resistant components, these solutions can significantly reduce climate change exposure.

Climate risk modelling has emerged as an essential tool for developers and investors to minimise their assets' climate risk exposure. In this space, Mitiga's product, EarthScan, offers location-specific hazard insights that guides smarter decision-making. EarthScan has proven to be effective in real-world scenarios as proven by the Capital Dynamics case study, showcasing how climate risk modelling is a profitable tool. Furthermore, climate risk modelling is proving to be essential across the energy industry and, as climate risks continue to intensify, climate risk modelling ensures long-term asset sustainability.

For these reasons, we encourage the EU and other global institutions to expand the integration of climate risk modelling into public policy. Regulations such as the CSRD (Corporate Sustainability Reporting Directive) and the TFCD (Task Force on Climate-related Financial Disclosure) are already important steps in the full implementation of climate risk modelling; nevertheless, there is still a long way to go.

By mandating the use of climate risk modelling platforms such as EarthScan, countries can ensure the future of their assets, solar or others, allowing them to successfully complete their future plans such as the case of REPowerEU in the European Union. To conclude, EarthScan is proven to be a major solution for the solar industry and beyond, highlighting the growing need for climate risk modelling across all sectors to ensure resilient infrastructure, informed investment and long-term sustainability in a changing climate.

