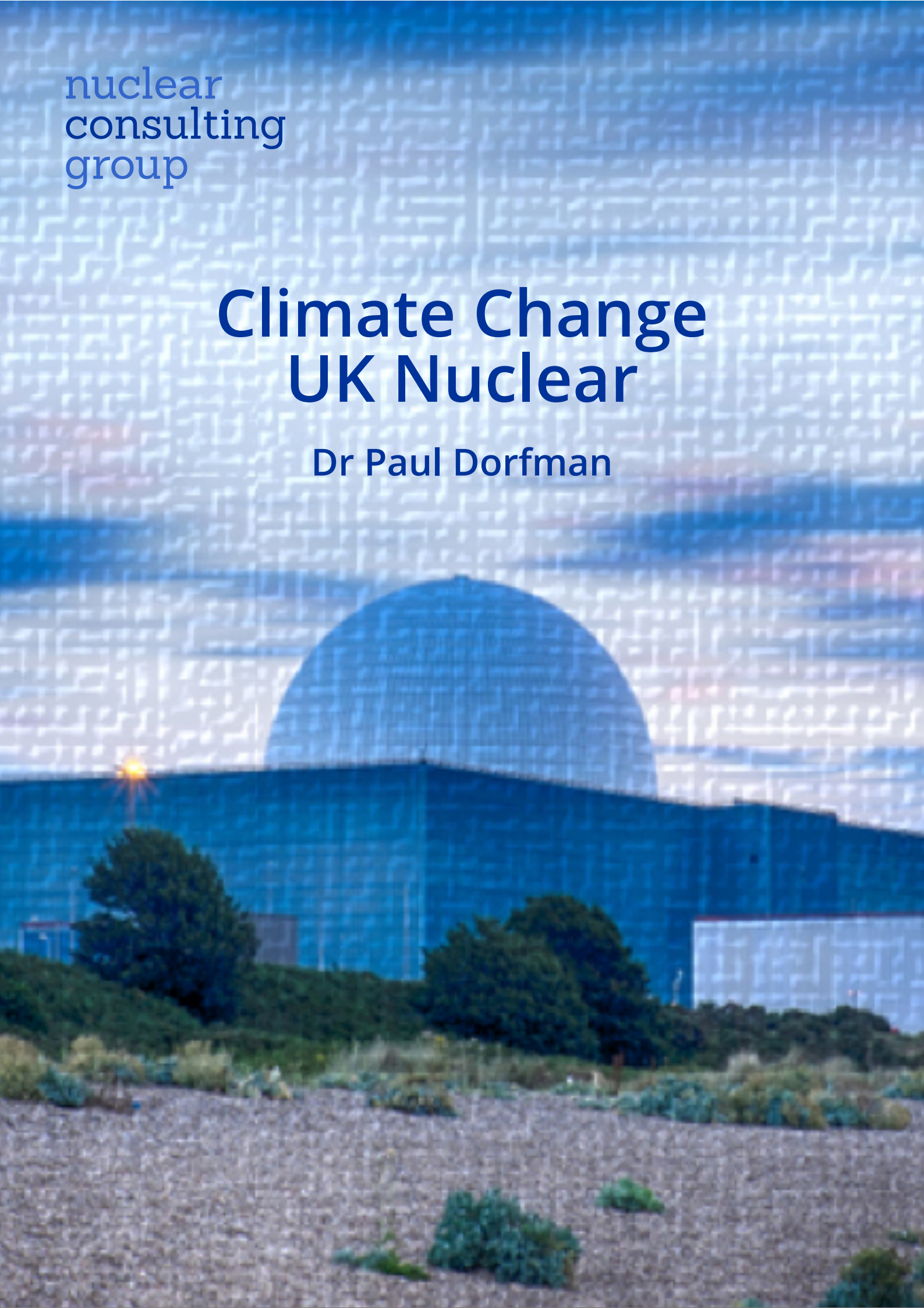


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Climate Change UK Nuclear

Dr Paul Dorfman



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Executive Summary

In the last year, climate models have run hot. As knowledge of enhanced climate sensitivity and polar ice melt-rate evolves, it has become clear that sea-level rise is significantly faster than previously thought, resulting in more frequent and destructive storm, storm surge, severe precipitation, and flooding.

With rare extreme events today becoming the norm in the future, existing risk mitigation measures become increasingly obsolete. The corollary to this analysis is that present and planned UK coastal nuclear installations will be at significant risk. In other words, nuclear's lower-carbon electricity USP sits in the context of the much larger picture – that UK coastal nuclear will be one of the first, and most significant, casualties to ramping climate impact. Put simply, UK nuclear is quite literally on the front-line of climate change – and not in a good way.

To better understand the scale of risk and deploying representative sea-level projections closely aligned with median IPCC findings based on only median sea-level projections; annual flood risk maps for the year 2050 at two representative UK nuclear installations are provided. Like all models, including those deployed by EDF and the Office for Nuclear Regulation (ONR), these coastal flood risk maps should be interpreted as plausible threat indicators requiring deeper investigation.

Integrating very recent peer-reviewed scientific knowledge on climate change impact, this Report's key finding is that UK civil nuclear infrastructure is profoundly unprepared for climate impact and there is a very high probability that reactors and their associated high-level spent fuel stores will become unfit for purpose.

Due to ramping climate induced sea-level rise, storm, storm surge, severe precipitation and raised river-flow, UK nuclear installations are set to flood – and much sooner than either the nuclear industry or regulators suggest. This is because risks to nuclear installations from sea-level rise driven extreme climate events will not be linear, as thresholds at which present natural and built environment coastal and inland flood defence barriers are exceeded.

Nuclear industry and ONR efforts to mitigate climate risk will involve significantly increased expense for any nuclear construction, operation, waste management, decommissioning, and even relocation or abandonment. Thus, it is essential that future climate risk to nuclear is transparently reassessed. In doing so, evolutionary modelled prediction of seasonal, decadal, and future climate change impact on nuclear infrastructure must be taken into account – including potential rapid change in extreme events, abrupt interactions and feedbacks.

Comprehensive ONR and nuclear industry risk assessments based on 'all case' scenarios should be published and regularly updated as fundamental scientific climate impact evidence evolves. Such an approach must include costings for any mitigation measures, and a range of contingency plans for the swift onset of climate-driven severe weather. In this sense, necessary action on climate change impact on UK nuclear infrastructure should be informed by and flow from the UK Presidency of COP 26 and the forthcoming Environment Bill, thereby reinforcing UK Fusion Doctrine.

1. Polar Ice-Caps are Melting

As the world heats, ice stored at the poles and in glaciers melt and sea levels rise¹. The rate of rise has accelerated in recent decades and is now estimated at 3 to 4mm a year.² With a recent NASA study based on 25 years of satellite data finding that global sea-level rise has been accelerating rather than increasing steadily, the Arctic is melting so rapidly that it's now 20% thinner than a decade ago, weakening a major source of the planet's cooling.³

The polar ice caps are melting six times faster than they were in the 1990s, with the high melt-rate corresponding to the worst-case scenario model for global heating set out by the Intergovernmental Panel on Climate Change (IPCC).⁴ This means that without sweeping curbs to CO₂ greenhouse gas emissions, the planet will see a very significant rise in sea-level, resulting in ramping annual coastal and inland flooding.^{5,6}

Meanwhile, satellite data shows the Greenland Ice Sheet has lost a record amount of ice in 2019 (equivalent to a million tons per minute). With the climate crisis heating the Arctic at double the rate in lower latitudes, the ice cap is currently the biggest single contributor to sea-level rise, and already imperils coasts and coastal populations.⁷

Here, it's unsettling to reflect that Greenland ice is melting faster than at any time in the past 12,000 years,⁸ shrinking by 532 billion tonnes last year, as its surface melts and

¹ The Guardian (Editorial) (2020): The Environment Now, Guardian, 2020.
<https://www.theguardian.com/environment/ng-interactive/2020/oct/05/climate-data-dashboard-carbon-atmosphere-sea-level-arctic-ice>

² Aschwanden A. (2020): The worst is yet to come for the Greenland ice sheet, Nature, Sept. 2020.
<https://www.nature.com/articles/d41586-020-02700-y>

³ NASA (2018): New Study Finds Sea Level Rise Accelerating, NASA, Feb. 2018.
<https://www.nasa.gov/feature/goddard/2018/new-study-finds-sea-level-rise-accelerating>

⁴ Hay F., Isla B., Marzeion, B., et al. (2019): Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Portner, D.C. Roberts, V. Masson-Delmotte, P. et al. (eds.)]. <https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/>

⁵ Shepherd A., Ivins E., Rignot, E., Smith, Ben et al. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature. 579 (7798): 233–239. <https://www.nature.com/articles/s41586-019-1855-2>

⁶ Horton B.P., Khan N.S., Cahill N., et al. (2020): Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey. *Clim Atmos Sci* 3, 18. <https://doi.org/10.1038/s41612-020-0121-5>

⁷ Sasgen I., Wouters B., Gardner A.S., et al. (2020): Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. *Commun Earth Environ* 1, 8 (2020).
<https://doi.org/10.1038/s43247-020-0010-1>

⁸ Turney C., Christopher J., Nicholas R. et al. (2020): Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica. *PNAS*. www.pnas.org/cgi/doi/10.1073/pnas.1902469117

glaciers fall into the ocean at a rate of seven Olympic-sized swimming pools per second⁹ – at a melt-rate matching any in the geological record for the Holocene (the period since the last Quaternary Ice Age).¹⁰

This is all the more concerning since very recent research reports new early-warning signals indicating that the central-western part of the Greenland Ice Sheet is undergoing a critical transition. Because of rising temperatures, the destabilization of the ice sheet has begun and the process of melting may escalate, substantially increasing global sea level rise. In other words, A significant part of the Greenland Ice Sheet is on the brink of a tipping point, after which accelerated melting would become inevitable.¹¹

And the Antarctic (where more than half of Earth's freshwater resources are held, representing by far the largest potential source for global sea-level rise under future warming conditions) is also threatened – with the likelihood that its long-term sea-level contribution will dramatically exceed that of other sources.¹²

It's worthwhile recalling that this has happened before, when a 2°C ocean warming was enough to destabilise Antarctica in the past, as rising ocean temperatures drove the melting of Antarctic ice sheets and caused extreme sea-level rise.¹³ New data from the Antarctic Blue Ice Field has found that the West Antarctic Ice Sheet has proven unstable during the last warm period (120,000 years ago),¹⁴ and it's now close to a stability tipping point, potentially resulting in a sea-level rise of 2.5 metres well within the 21st century even if the goals of the Paris Climate Agreement are met.¹⁵

⁹ The IMBIE Team (2019): Mass balance of the Greenland Ice Sheet from 1992 to 2018, Nature <https://doi.org/10.1038/s41586-019-1855-2>, Nature, 2019. <https://www.nature.com/articles/s41586-019-1855-2>

¹⁰ Briner J.P., Cuzzone J.K., Badgley J.A. et al. (2020): Rate of mass loss from the Greenland Ice Sheet will exceed Holocene values this century. Nature 586, 70–74 (2020). <https://www.nature.com/articles/s41586-020-2742-6#citeas>

¹¹ Boers N. and Rypdal M. (2021): Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point, Proceedings of the National academy of Sciences of the United States of America, 2021. <https://www.pnas.org/content/118/21/e2024192118>

¹² Garbe J., Albrecht T., Levermann A., et al. (2020): The Hysteresis of the Antarctic Ice Sheet, 538 | Nature | Vol 585 | September 2020. <https://www.nature.com/articles/s41586-020-2727-5.epdf>

¹³ Landow S. (2020): Ancient Arctic ice melt increased sea levels by 3+ metres – and it could happen again, UNSW, Feb 2020. <https://newsroom.unsw.edu.au/news/science-tech/ancient-antarctic-ice-melt-increased-sea-levels-3-metres-%E2%80%93-and-it-could-happen>

¹⁴ The Eemian warm period was the last phase of climate history with global temperatures similar to those that the world is heading towards due to man-made global warming in the coming decades.

¹⁵ Levermann A., Winkelmann R., Albrecht T., et al. (2020): Projecting Antarctica's contribution to future sea level rise from basal ice shelf melt using linear response functions of 16 ice sheet models (LARMIP-2), Earth Syst. Dynam., 11, 35–76. DOI: 10.5194/esd-11-35-2020. <https://www.earth-syst-dynam.net/11/35/2020/>

Further very recent analysis deploying satellite observations and numerical models demonstrate that the combined Arctic and Antarctic ice masses lost 28 trillion tonnes of ice between 1994 – 2017 (equivalent to a sheet of ice 100 metres thick covering the whole of the UK), with ice loss rising by 57% since the 1990s¹⁶ – a rate of loss in line with worst-case IPCC scenarios.¹⁷

Put simply, current fundamental scientific knowledge of climate sensitivity and polar ice melt concludes that sea-level rise is significantly faster than previously believed and likely to exceed up to 2.5 metres well within the 21st century.¹⁸

1.1 Climate Models Run Hot

Evolving knowledge based on significantly improved models of coastal sea-level elevations provide new best estimates of climate impact vulnerability,¹⁹ and although model uncertainty is a key challenge,²⁰ a fifth of new results published in the last year have come in with anomalously high climate sensitivity – implying that Paris Climate Agreement goals may already be out of touch.²¹

However, even current climate worst-case models may not capture the potential risk, as very recent cloud data suggests the climate is considerably more sensitive to carbon emissions than thought. Compared to the last IPCC assessment in 2014, a substantive number of climate studies demonstrate a sharp upward shift from 3°C to 5°C in climate sensitivity – the amount of warming projected via a doubling of atmospheric carbon dioxide from the pre-industrial level of 280 parts per million CO₂.²²

¹⁶ Slater T., Lawrence I. R., Otosaka I. N., et al. (2021): Earth's ice imbalance, Review article: The Cryosphere, 15, 233–246, <https://doi.org/10.5194/tc-15-233-2021>, 2021.

¹⁷ Schulz F. (2019): IPCC drastically increases its forecasts for world's rise in sea levels, Euractiv, Sept 2019. <https://www.euractiv.com/section/energy-environment/news/ipcc-drastically-increases-its-forecasts-for-worlds-rise-in-sea-levels/>

¹⁸ Kulp S.A., Strauss B.H. (2019): New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat Commun* 10, 4844 (2019). <https://doi.org/10.1038/s41467-019-12808-z>

¹⁹ Scott A., Kulp S.A. & Strauss B.H. (2019): New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding, *Nature*. <https://www.nature.com/articles/s41467-019-12808-z.pdf>

²⁰ Kopp R. E., et al. (2017): Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections. *Earth's. Future* 5, 1217–1233.

²¹ Roston E. (2020): Climate Models Are Running Red Hot, and Scientists Don't Know Why, *Bloomberg Green*, Feb 2020. <https://www.bloomberg.com/news/features/2020-02-03/climate-models-are-running-red-hot-and-scientists-don-t-know-why>

²² Intergovernmental Panel on Climate Change (IPCC) (2020): AR6 Climate Change 2021: Impacts, Adaptation and Vulnerability The Working Group II contribution to the Sixth Assessment Report. <https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/>

It's sobering to reflect that a net loss of 600 billion tonnes was enough to raise the global watermark to about 40% of total sea-level rise in 2019.²³ And, perhaps incredibly, the Greenland Ice Sheet (which, until the end of the 20th century accumulated as much mass as it shed) holds enough frozen water to lift the world's oceans by 7 metres. Note, over half the dramatic ice sheet loss in 2019 was due not to warmer-than-average air temperatures but unusual high-pressure weather systems linked to global warming.²⁴

Further, a key atmospheric CO₂ pathway may be missing from current models. This is because, since carbon from thawing permafrost is flushed into waterways and converted to CO₂ by sunlight, present climate models may underestimate CO₂ emissions from permafrost by up to 14% – and, as a consequence, current estimates of additional global warming and sea-level rise from permafrost carbon feedback may prove too low.²⁵

This resonates with research commissioned by the Delta Programme at the Dutch Deltares Centre (tasked with protecting Holland against flooding and sea-level change), which suggest sea-level rise in the North Sea may accelerate sharply from 2050 – and that the UK should be preparing for its seas, estuaries and tidal rivers to rise by up to 2 metres in the next 80 years²⁶ (nearly double the UK Met Office's worst-case predictions).²⁷ Perhaps disconcertingly, the Delta report adds that the more rapid melting of Antarctic ice sheets haven't yet been incorporated into their programme's predictions.

Similarly, a recent review of global climate model estimates find they fall below observational records, suggesting that the likely upper level of sea rise projections in current IPCC reports will be too low. In other words, sea-levels are rising faster than IPCC worse-case forecasts.²⁸

²³ Sasgen I., Wouters B., Gardner A.S., et al. (2020): *ibid.*

²⁴ Hood M. (2020): Alarms ring as Greenland ice loss causes 40% of 2019 sea level rise, PhysOrg. <https://phys.org/news/2020-04-alarms-greenland-ice-loss-sea.html>

²⁵ Bowen J.C., Ward C.P., Kling G.W., & Cory R.M. (2020): Arctic Amplification of Global Warming Strengthened by Sunlight Oxidation of Permafrost Carbon to CO₂, *Geophysical Research Letters*, Open Access, June 2020. <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020GL087085>

²⁶ Leake J. (2020): Think the flooding is bad now? Britain faces 6ft rise in sea level, warns Dutch expert, *The Times*, Feb 2020. <https://www.thetimes.co.uk/article/think-the-flooding-is-bad-now-britain-faces-6ft-rise-in-sea-level-warns-dutch-expert-gl6mlvvqq>

²⁷ UK Met. Office (2020): UK Climate Projections (UKCP), 2020. <https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index>

²⁸ Grinsted, A. and Christensen, J. H. (2021): The transient sensitivity of sea level rise, *Ocean Sci.*, 17, 181–186, 2021. <https://doi.org/10.5194/os-17-181-2021>, 2021.

And the world's oceans are heating, reaching their hottest level in recorded history, supercharging the extreme weather impacts of the climate emergency.²⁹ With summer sea ice declining due to amplified warming,³⁰ the oceans are heating faster than any time in the last 2,000 years, providing more energy to storms and storm surge, making them significantly more frequent and severe.

1.2 Storm Surge

The effect of rising mean sea-levels at coastal installations will be felt most profoundly during extreme storm conditions when strong winds and low atmospheric pressure bring about a temporary and localised increase in sea-level known as a 'storm surge'.³¹

In other words, it's not just the height of the rise in sea-level that's important, it's also the increase in storm surge. And as the British Oceanographic Data Centre Global Extreme Sea-Level Analysis project notes,³² the magnitude and frequency of extreme sea-levels (a factor of mean sea-level, tide and storm-induced increase) which can cause storm surge and catastrophic flooding, has accelerated world-wide.³³

Since coastal areas epitomise 'at risk' territory to climate change and sea-level rise,³⁴ knowledge of coastal sea-level change from mean sea-level variability, tide, atmospheric surge and wave set-up are critical for coastal flooding assessment, including how coastal water level alters this combined interaction.³⁵

²⁹ Gebbie G. (2021): Combining Modern and Paleooceanographic Perspectives on Ocean Heat Uptake. *Ann Rev Mar Sci.* Jan 2021; 13:255-281. doi: 10.1146/annurev-marine-010419-010844. Epub 2020 Sep 14. PMID: 32928022.

³⁰ Cai Q., Wang J., Beletsky D., et al (2021): Summer Arctic sea ice decline during 1850-2017 and the amplified Arctic warming during the recent decades, *IOP Science*, Jan 2021. <https://iopscience.iop.org/article/10.1088/1748-9326/abdb5f>

³¹ Storm surge is sea water pushed toward the shore by the force of storm winds. This advancing surge combines with normal tides to create a storm tide, which can increase the mean water level by 15 feet or more. In addition, wind-driven waves can be superimposed on the storm tide, causing further risk.

³² British Oceanographic Data Centre (2018): GESLA (Global Extreme Sea Level Analysis) high frequency sea level dataset – Version 2. <https://data-search.nerc.ac.uk:443/geonetwork/srv/api/records/19e0ccb8e575a139b7b70a6e875ef8b>

³³ Kirezci E., Young I.R., Ranasinghe R. et al. (2020): Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Sci Rep* 10, 11629 (2020). <https://doi.org/10.1038/s41598-020-67736-6>

³⁴ Donovan B., Horsburgh K, Ball T., & Westbrook G. (2013): Impacts of climate change on coastal flooding, *MCCIP Science Review* 2013: 211-218. http://www.mccip.org.uk/media/1279/2013arc_sciencereview_22_cf_final.pdf

³⁵ Edwards T. (2017): Future of the Sea: Current and Future Impacts of Sea Level Rise on the UK, Foresight: Government Office for Science. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/663885/Future_of_the_sea_-_sea_level_rise.pdf

High tides cause significant modifications, modulating wave set-up. Yet, although cumulative interactions have significant implications for changes in the frequency and height of future extreme tide and storm surge, climate impact projections are deeply under-rehearsed – including those for civil nuclear installations.³⁶

³⁶ Idier D., Bertin X., Thompson P., & Pickering M. (2020): Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast. *Surveys in Geophysics*, Springer Verlag. <https://hal-brgm.archives-ouvertes.fr/hal-02167224/document>

2. UK Climate Impact

Rising sea levels, modified rainfall patterns and extreme temperatures have been forecast in the UK Climate Change Risk Assessment Report,³⁷ with flooding expected to be one of the most prominent climate change risks to people, communities and infrastructure.³⁸

More recently, the Chair of the UK Environment Agency (EA) stated that even if we reach net zero by 2050, summer temperatures are set to be up to 7.4 °C hotter, there will be 59% more winter rainfall, and once-a-century sea-level events are to be expected on an annual basis.³⁹ Perhaps disconcertingly, whilst preparing for a 2°C rise in global temperatures, the EA are also planning for a potential 4°C rise by 2100.⁴⁰

Similarly, a set of detailed European Environment Agency (EEA) maps emphasise the scale of climate impact that the EU and the UK will face if urgent action isn't taken to confront global heating,⁴¹ suggesting an upper bound for global mean sea-level rise in the range of up to 2.5 metres – significantly increasing coastal flooding.⁴²

³⁷ HM Government (2017): UK Climate Change Risk Assessment, HMG, 2017.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/584281/uk-climate-change-risk-assess-2017.pdf

³⁸ Kovats R., Osborn D. (2016) UK Climate Change Risk Assessment 2017: Evidence Report. Chapter 5: People & the built environment. Adaptation Sub-Committee of the Committee on Climate Change: London, UK. <https://discovery.ucl.ac.uk/id/eprint/1564649/>

³⁹ Boyd H.E. (Chair of the Environment Agency) (2020): Climate change and water: Are we doing enough, fast enough? Speech to the Institute of Water, Nov 2020. <https://www.gov.uk/government/speeches/climate-change-and-water-are-we-doing-enough-fast-enough--2>

⁴⁰ Environment Agency (EA) (2020): National Flood and Coastal Erosion Risk Management Strategy for England, Policy paper, EA, Sept. 2020. <https://www.gov.uk/government/publications/national-flood-and-coastal-erosion-risk-management-strategy-for-england--2>

⁴¹ European Environment Agency (EEA) (2020): Climate Change Impacts in Europe, EEA, Feb 2020. <https://experience.arcgis.com/experience/5f6596de6c4445a58aec956532b9813d>

⁴² Rankin J. (2020): Fires and floods: maps of Europe predict scale of climate catastrophe: Without urgent action, rising sea levels by end of century could leave cities under water, The Guardian, 2020. <https://www.theguardian.com/environment/2020/feb/10/fires-floods-maps-europe-climate-catastrophe>

2.1 Coastal Flooding

Projected climate-induced changes in flood frequency mean that extreme events today are very likely to become the norm in the future, with coastal flooding frequency estimated to increase by a factor of between 10 and more than 100 in many European locations, depending on the emissions scenario.⁴³

Meanwhile, the European Commission's Joint Research Centre concludes that the UK is on course to lose 1,531 km (27.7%) of its sandy coast in a best-case scenario, and 2,415 km (43.7%) in a worst-case.⁴⁴ And similar trends may occur globally, with ambient movement in shoreline dynamics combined with coastal recession driven by sea-level rise resulting in severe damage to almost half the planet's sandy beaches by the end of the century in a worst-case scenario that assumes only an 80cm rise in sea-level.⁴⁵

Although these estimates can be set against a forecast of international action on climate breakdown (known as the Representative Concentration Pathway 4.5,⁴⁶ where reduced ice-cap melt and lower thermal expansion of water results in only a 50cm sea-level rise by 2100)⁴⁷ – to do so seems optimistic, especially considering 'combined hazard' impact.

2.2 Combined Hazard

Sea-level rise and predicted changes to UK storm patterns (affecting both storm surge and river flow) will alter the probability of multiple hazard events, making previous understanding of risk and mitigation measures obsolete. This is because existing probabilistic methods for assessing combination hazard provide only limited detail on where and when risks may occur and can't accommodate revised event distributions due to climate change-driven sea-level rise.⁴⁸

⁴³ European Environment Agency (EEA) (2020): *ibid.*

⁴⁴ Webster B. (2020): Rising seas would destroy 1,000 miles of UK beaches, *Times*, Mar 2020. <https://www.thetimes.co.uk/article/rising-seas-threaten-nearly-half-of-uks-beaches-cw8mcmxr6>

⁴⁵ Vousdoukas M.I., Ranasinghe R., Mentaschi L., et al. (2020): Sandy coastlines under threat of erosion. *Nat. Clim. Chang.* 10, 260–263 (2020). <https://doi.org/10.1038/s41558-020-0697-0>

⁴⁶ A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC.

⁴⁷ Thomson A.M., Calvin K.V., Smith S.J., et al. (2011): RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Climatic Change* 109, 77 (2011). <https://doi.org/10.1007/s10584-011-0151-4>.

⁴⁸ Lewis M.J., Palmer T., Hashemi R., et al. (2019): Wave-tide interaction modulates nearshore wave height. *Ocean Dynamics* 69, 367–384 (2019). <https://doi.org/10.1007/s10236-018-01245-z>

Thus, combined hazards present a clear and present danger to coastal infrastructure – with 2,013 ports world-wide at risk from multiple hazards as coastal flooding, wave overtopping and storm surge increases.⁴⁹

2.3 So What

Taking all this into consideration, it seems clear that the low-lying parts of the UK coast will be at significant and ramping risk from climate impact – and much sooner than expected.

In other words, recent peer-reviewed published scientific data point to much quicker and greater sea-level rise, faster, harder, more destructive storm and storm surge; inevitably bringing into question the operational safety, security and viability of low-lying UK coastal infrastructure.

⁴⁹ Izaguirre C., Losada I.J., Camus, P., et al. (2021): Climate change risk to global port operations. *Nat. Clim. Chang.* 11, 14–20 (2021). <https://doi.org/10.1038/s41558-020-00937-z>

3. Climate Change Nuclear Vulnerability

Following the UK government determination that all civil nuclear infrastructures were uniquely implicated in all four high priority tier-one threats identified in the National Security Strategy,⁵⁰ NATO's 2017 Strategic Foresight Analysis reported that climate change is a 'threat multiplier' involving both sea-level rise risk to coastal regions and increased impact of storm surge and inland inundation events.⁵¹

3.1 Beyond Design-Base

Although near-term climate change risk to nuclear power plant seems very great,⁵² the overwhelming majority of installed nuclear capacity began operation well before global heating was considered in design or construction.

Now, with ramping predictions for sea-level rise and climatic disturbance, nuclear will prove an important risk in the UK and internationally.⁵³ This is because 41% of all nuclear power plants world-wide operate on the sea-coast, making them vulnerable to increasing sea-level rise, storm intensity and storm surge induced flooding.⁵⁴

Inland nuclear plant face other climate risks, including increasingly severe wildfire, with episodic flooding events alternating with low river-flow and raised water temperature – the latter significantly impacting on reactor cooling capacity and, hence, viability.

Since climate change will impact nuclear plant earlier and harder than industry, government or regulatory bodies may expect,⁵⁵ efforts to mitigate global heating risk to nuclear will mean significantly increased expense for nuclear construction, operation

⁵⁰ HM Government (2010): A Strong Britain in an Age of Uncertainty: The National Security Strategy, Presented to Parliament by the Prime Minister, October 2010, Cm. 7953, Stationery Office, London.

⁵¹ NATO (2017): Strategic Foresight Analysis, NATO, 2017.
https://www.act.nato.int/images/stories/media/doclibrary/171004_sfa_2017_report_hr.pdf

⁵² Anderson J. (2019): Nuclear plant climate change risk assessment, action plans needed: researchers, S&P Platts, 2019. <https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/111219-nuclear-plant-climate-change-risk-assessment-action-plans-needed-researchers>

⁵³ Shifflett S., Sheppard K. (2017): How Rising Seas Could Sink Nuclear Plants On The East Coast, Huffpost, 05/19/2014, Dec 2017. https://www.huffpost.com/entry/maps-rising-seas-storms-threaten-flood-coastal-nuclear-power-plants_n_5233306

⁵⁴ Nunez C. (2015): As Sea Levels Rise, Are Coastal Nuclear Plants Ready? Some low-lying plants face a watery future, but the legacy of Fukushima is spurring action, National Geographic. 2015. <https://www.nationalgeographic.com/news/energy/2015/12/151215-as-sea-levels-rise-are-coastal-nuclear-plants-ready/>

⁵⁵ Nerem R.S., Beckley B.D., Fasullo J.T., et al. (2018): Climate-change-driven accelerated sea-level rise, Proceedings of the National Academy of Sciences Feb 2018, 115 (9) 2022-2025; DOI: 10.1073/pnas.1717312115. <https://www.pnas.org/content/115/9/2022>

and decommissioning.⁵⁶ And since coastal spent fuel management facilities are vulnerable to unanticipated environmental events,⁵⁷ climate change and accompanying sea-level rise are set to create significant risk to on-site high, medium and low-level nuclear waste stockpiles.

A key associated problem is that 516 million people world-wide live within a fifty mile (80km) radius of at least one operating nuclear power plant, and 20 million live within a ten mile (16km) radius – and so face health and safety risks from climate change-induced radiation contamination release events.⁵⁸ Since at least 100 nuclear power stations have been built just a few meters above sea-level and will be increasingly threatened by serious flooding caused by accelerating sea-level rise and more frequent storm surge, there's no question but nuclear stations are, quite literally, on the front-line of climate change risk.⁵⁹

For example, the U.S. Nuclear Regulatory Commission (NRC) concludes that 55 of 61 U.S. nuclear sites have already experienced flooding hazard beyond their design-base,⁶⁰ and a recent U.S. Army War College report states that nuclear power facilities are at 'high risk' of temporary or permanent closure due to climate threats – with 60% of U.S. nuclear capacity vulnerable to major risks including sea-level rise, severe storms, and cooling water shortages.⁶¹ In response, although the U.S Nuclear Energy Agency (NEA) is conducting an as yet unpublished study on nuclear power plant vulnerability to climate

⁵⁶ Kopytko N. & Perkins J. (2011): Climate change, nuclear power, and the adaptation-mitigation dilemma, *Energy Policy*, Volume 39, Issue 1, pp. 318-333. Jan 2011, <https://www.sciencedirect.com/science/article/abs/pii/S0301421510007329>

⁵⁷ Jenkins M.J., Alvarez R., & Jordaan S.M. (2020): Unmanaged climate risks to spent fuel from U.S. nuclear power plants: The case of sea-level rise, *Energy Policy*, Vol 137, Feb 2020. <https://www.sciencedirect.com/science/article/abs/pii/S0301421519306937#>

⁵⁸ Jordaan S.M., Siddiqi A., Kakenmaster W., & Hill A.C. (2019): The Climate Vulnerabilities of Global Nuclear Power, *Massachusetts Institute of Technology (MIT), Global Environmental Politics*, Volume 19, Issue 4, p.3-13, Nov 2019. https://www.mitpressjournals.org/doi/abs/10.1162/glep_a_00527

⁵⁹ Vidal J. (2018): Are Coastal Nuclear Power Plants Ready for Sea Level Rise? *Hakai*: Aug 2018. <https://www.hakaimagazine.com/features/are-coastal-nuclear-power-plants-ready-for-sea-level-rise/>

⁶⁰ Flanders S., Chokshi N. et al. (2017): Insights Gained from Post Fukushima Reviews of Seismic and Flooding Hazards at Operating U.S. Nuclear Power Plant Sites, *Transactions, SMiRT-24 BEXCO, Busan, Korea* – August 20-25, 2017 Division VII.

⁶¹ United States Army War College (2019): Implications of Climate Change for the U.S. Army, 2019. https://climateandsecurity.files.wordpress.com/2019/07/implications-of-climate-change-for-us-army-army-war-college_2019.pdf

change,⁶² active protective or adaptation measures remain uncoded and unprioritised.⁶³

3.2 Investment, Relocation, Abandonment

Whilst it seems clear that climate change-driven coastal flooding will impact UK nuclear power stations, the key questions are when and by how much? Well, the UK Institute of Mechanical Engineers (IME) state that all existing and proposed new UK reactors (together with their spent nuclear fuel and radioactive waste stores) will be increasingly vulnerable to sea-level rise, flooding, storm surge, and 'nuclear islanding'.⁶⁴ Perhaps alarmingly, IME point out that these UK coastal nuclear sites will need considerable investment to protect them against rising sea levels, and even relocation or abandonment.⁶⁵

And according to an unpublished UK government document obtained some time ago under the Freedom of Information Act,⁶⁶ the Environment Agency have warned that 12 of UK's 19 nuclear sites are in danger of coastal flooding and erosion.⁶⁷ Nine of the sites were assessed as vulnerable, while others are at risk from rising sea levels, storm surge and combined hazard compound flooding (when storm surge combines with heavy rainfall) – since not only is storm surge made worse with heavy precipitation, but it can also block or slow river drainage to the sea.⁶⁸

⁶² U.S. Nuclear Energy Agency (NEA) (Ongoing): Expert Group on Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Cost of Adaptation (NUCA), NEA. https://www.oecd-nea.org/jcms/pl_28742/ad-hoc-expert-group-on-climate-change-assessment-of-the-vulnerability-of-nuclear-power-plants-and-cost-of-adaptation-nuca

⁶³ Chen C. (2019): Nuclear vs. Climate Change: Rising Seas, Expert Blog, NRDC – Alum, Sept. 2019. <https://www.nrdc.org/experts/christina-chen/nuclear-vs-climate-change-rising-seas>

⁶⁴ 'Nuclear islanding' occurs when the nuclear power plant is completely surrounded by flood water.

⁶⁵ Institute of Mechanical Engineers (IME) (2009): Climate Change: Adapting to the Inevitable, IME 2009. <https://www.imeche.org/policy-and-press/reports/detail/climate-change-adapting-to-the-inevitable>

⁶⁶ Scribd: Nuclear Sites. <https://www.scribd.com/document/84289220/Nuclear-sites>

⁶⁷ Brown P. (2018): Weatherwatch: the nuclear option and rising levels of anxiety, Guardian, June 2018. <https://www.theguardian.com/news/2018/jun/22/weatherwatch-the-nuclear-option-and-rising-levels-of-anxiety>

⁶⁸ Edwards R. (2012): UK nuclear sites at risk of flooding, report shows, Guardian, Mar 2012. <https://www.theguardian.com/environment/2012/mar/07/uk-nuclear-risk-flooding>

3.3 ONR Unknown Knowns

Whilst the UK Office for Nuclear Regulation (ONR) Nuclear Safety Technical Assessment Guide on External Hazards highlights the fact that changes in meteorological and coastal flooding hazards from climate change could be significant,⁶⁹ ONR only assess nuclear 'Safety Cases'⁷⁰ with the expectation that 'reasonably foreseeable' effects are taken into account. The problem is, even though ONR's Expert Panel on External Hazards reports that there will be a significant increase in sea-level rise events by 2050 – ONR doesn't define what a reasonably foreseeable sea-level rise could be, and so this remains the responsibility of the nuclear power plant industrial corporate owner to justify.

As ONR's Expert Panel admits, projections for climate impact contain 'considerable uncertainty', with small changes to UK storm systems altering the height of storm surges significantly.⁷¹ This is all the more worrying due to the very real possibility of unexpected rapid extreme events from abrupt climate change, including unaccounted-for interactions and feed-backs. Even more inexplicably, ONR maintain that nuclear power plant owners don't have to reconsider their key nuclear safety case in the light of new climate science.⁷²

In this context, it's unsettling to reflect that very recent research (not based on the theoretical relationships suggested by atmospheric physics, but on historical climate data) allows climate sensitivity uncertainty to be estimated from direct observations with few assumptions. Grounded on historical data, the Scaling Climate Response Function model significantly reduces prediction uncertainties.⁷³ In analysing the results, the research finds that the +1.5°C threshold for dangerous warming will likely be crossed between 2027 – 2042, and all that implies for sea-level rise, storm surge and, hence, current ONR regulation of climate related nuclear risk based on their 'reasonably foreseeable' event standard.⁷⁴

⁶⁹ UK Office for Nuclear Regulation's (ONR) (2018): Nuclear Safety Technical Assessment Guide on External Hazards, ONR, Oct. 2018. http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013.pdf

⁷⁰ A nuclear Safety Case identifies the hazards and risks that face an operating nuclear power plant and describes the safety management systems that attempt to mitigate them. It provides the evidence on which ONR judges whether a nuclear facility is adequately safe to operate (or not) and is a key nuclear site licence condition.

⁷¹ UK Office for Nuclear Regulation (ONR) Expert Panel on Natural Hazards (2017): Analysis of Coastal Flood Hazards for Nuclear Sites, Expert Panel Paper No: GEN-MCFH-EP-2017-2, Sub-Panel on Meteorological & Coastal Flood Hazards. NS-TAST-GD-013, Annex 3 Reference Paper. http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013-annex-3-reference-paper.pdf

⁷² UK Office for Nuclear Regulation (ONR) (2019): Sea Level Rises, Request number 201801052, Release of information under Freedom of Information Act 2000, Information requested and released, Feb 2019. <http://www.onr.org.uk/foi/2019/201901052.htm>

⁷³ Hébert R., Lovejoy S., & Tremblay B. (2020): An observation-based scaling model for climate sensitivity estimates and global projections to 2100. *Clim Dyn*, 2020. <https://doi.org/10.1007/s00382-020-05521-x>

⁷⁴ UK Office for Nuclear Regulation's (ONR) & Environment Agency (EA) (2017): Principles for flood and coastal erosion risk management, ONR & EA, 2017. <http://www.onr.org.uk/documents/2017/principles-for-flood-and-coastal-erosion-risk-management.pdf>

4. Form, Function and Flooding

Given the significant risks associated with UK nuclear installation operations combined with their substantive radioactive waste inventories – it could prove important to better understand any reasonably foreseeable climate-driven impact these facilities are likely to face in the future.

Here, two representative practical examples may prove helpful: The ageing nuclear power plant at Dungeness (Kent), and proposed new nuclear reactor construction at Sizewell C (Suffolk).

Deploying representative sea-level projections closely aligned with only median IPCC findings,⁷⁵ and based on only median sea-level projections⁷⁶ – the Climate Central derived annual flood risk maps⁷⁷ should be interpreted as threat indicator screening tools requiring deeper investigation.⁷⁸ This is because, despite the relative limitations of all modelled data, the underpinning analysis deploys significantly improved consideration of coastal elevation, ocean thermal expansion, ice sheet melt, and land motion – and, hence, provides good estimates of vulnerability to sea-level rise induced climate impact.

As discussed, new knowledge concerning the role of enhanced sensitivity of Greenland and especially Antarctic ice sheets to global warming (and hence sea-level rise) give very significant cause for concern. In this context, it's important to note that the flood risk maps focus on only median projections from a sea-level rise model that doesn't incorporate the higher end of potential ice sheet sensitivity. Thus, since the following maps are based on the conservative Representative Concentration Pathway (RCP) predictions consistent with the Paris Climate Agreement's 2°C target,⁷⁹ they represent both reasonable and plausible projections – and are certainly equivalent to comparable nuclear industry and regulatory modelled forecasts.

⁷⁵ Stocker T. et al. *Climate Change (2013): The Physical Science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, 2013.

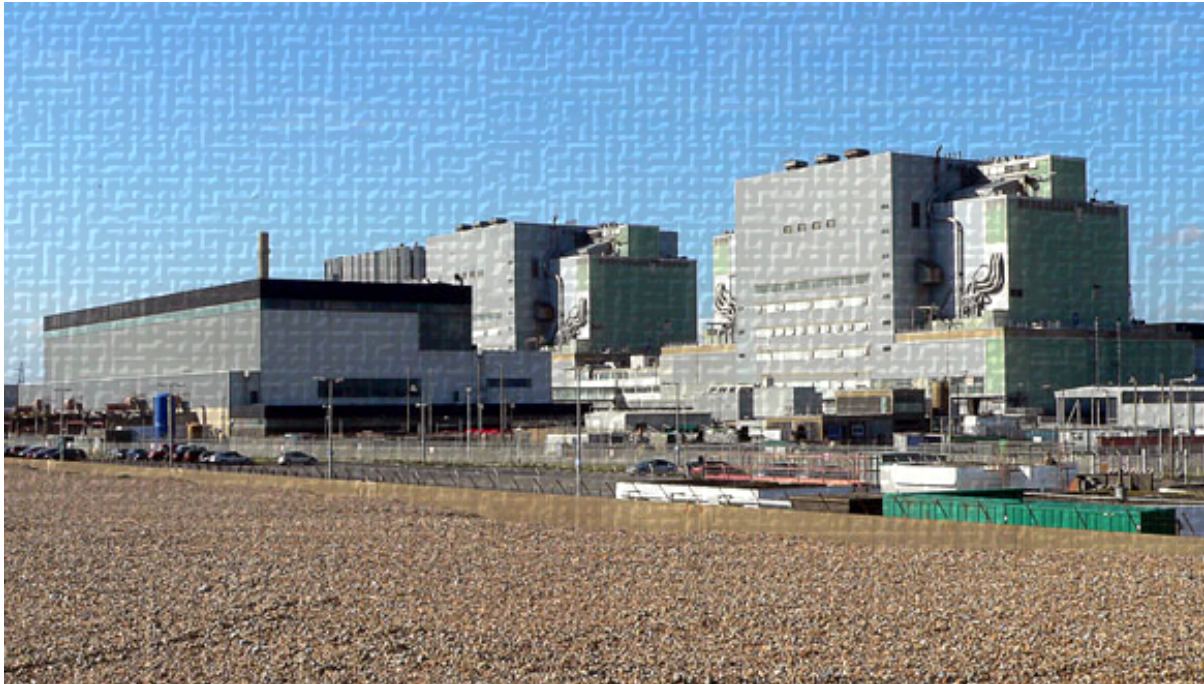
⁷⁶ Church J.A., Clark P.U., Cazenave A., et al (2013): Sea-Level Rise by 2100, *Science*, Vol. 342, Issue 6165, pp. 1445, Dec 2013, DOI: 10.1126/science.342.6165.1445-a

⁷⁷ Climate Central: Interactive Threat Maps at <https://coastal.climatecentral.org>

⁷⁸ Climate Central (2019): *Flooded Future: Global Vulnerability to Sea Level Rise Far Worse Than Previously Understood*, Report by Climate Central, Oct 2019. <https://www.climatecentral.org/pdfs/2019CoastalDEMReport.pdf>

⁷⁹ Kopp R. E., Horton R.M., Little C.M., et al (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, 2, 383–406. 2014. doi:10.1002/2014EF000239

4.1 Dungeness EDF Nuclear Power Plant



Électricité de France (EDF) Dungeness nuclear station, located on the Dungeness headland, comprises a legacy Magnox plant and an AGR nuclear plant of two 1496 MWt reactors which (although non-operational due to ongoing safety concerns) have had their operating licenses renewed until 2028, with decommissioning projected to last up to 2088. This, despite the fact that, as a recent report Commissioned by Kent County Council notes: Sea-level rise will substantially alter the site, which is low-lying and less than 70m from the current mean high-water mark.⁸⁰

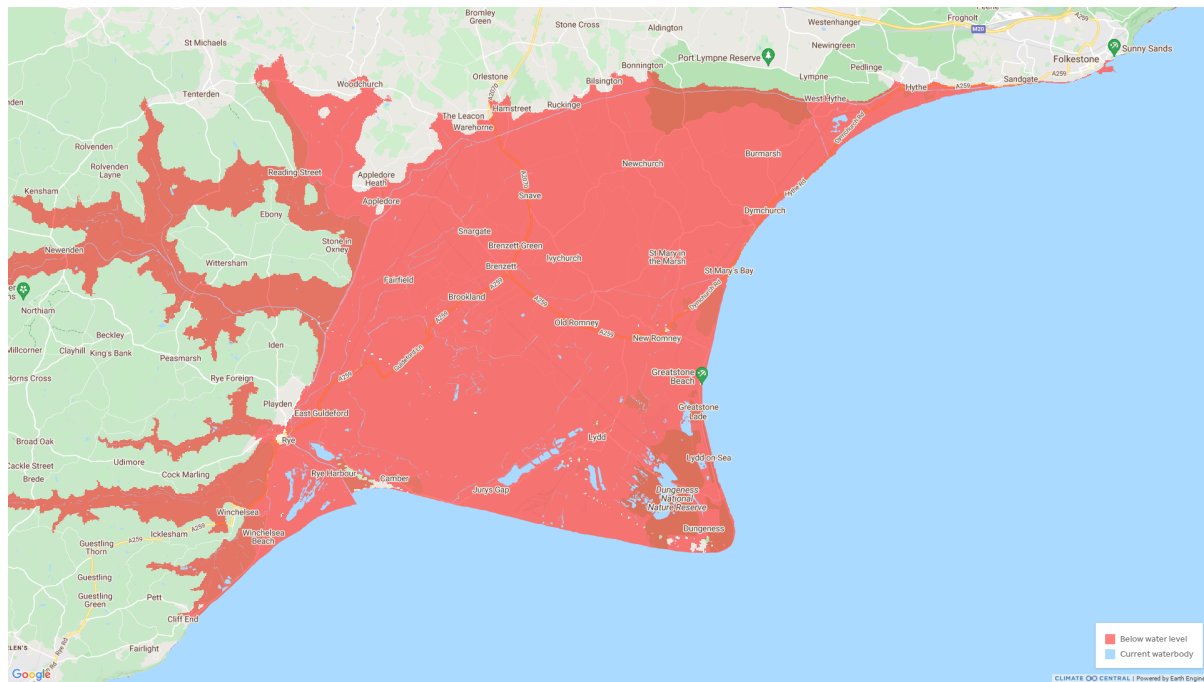
Moreover, the Kent County Council report states that with projected changes in sea-level and under combined hazard conditions (where coastal flooding meets high wind), radiation contamination following an accident or incident could significantly impact the South East UK population and further afield.⁸¹

Keeping this in mind, it's disconcerting to reflect that there's a very high probability that the nuclear power plant will be subject to very significant near-term annual flood risk – See Fig.1.

⁸⁰ JBA Consulting for Kent County Council (2020): Climate Change Risk and Impact Assessment for Kent and Medway, Part 2: Utilities Sector Summary, KCC & EC Interreg North Sea Regional Development Fund, FRAMES, June 2020. https://www.kent.gov.uk/__data/assets/pdf_file/0003/111387/CCRIA-for-Kent-and-Medway-part-two-utilities-sector-summary.pdf

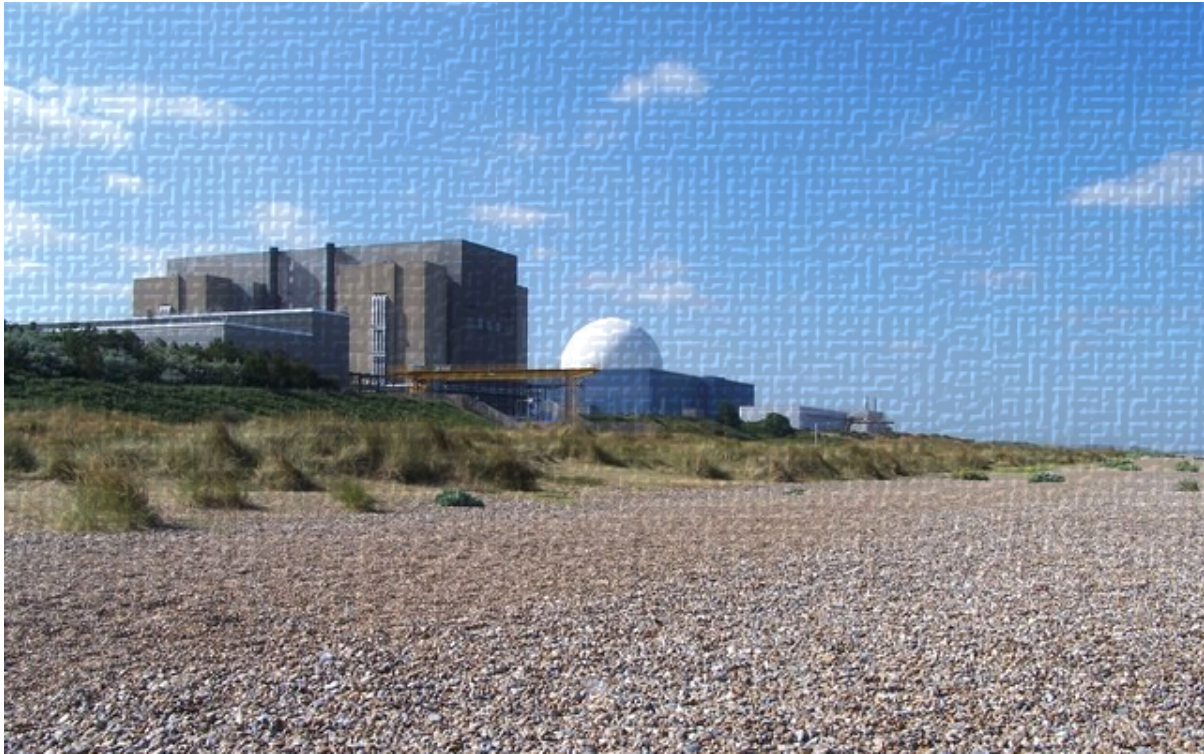
⁸¹ JBA Consulting for Kent County Council (2020): *ibid.*

Fig. 1 Dungeness Nuclear Power Plant Annual Flood Risk Map 2050⁸²



⁸² Annual flood level: Water level at shoreline that local coastal floods exceed on average at least once per year at 2050. Emissions pathway: Moderate emissions cuts (RCP 4.5) consistent with the Paris Climate Agreement 2°C target, median climate sensitivity. Elevation model: CoastalDEM.

4.2 Proposed Sizewell C EDF EPR Nuclear Power Plant



With UK's Department for Business, Energy & Industrial Strategy (BEIS) considering exploring investing in a nuclear project 'subject to clear value for money for consumers and taxpayers',⁸³ EDF have submitted plans to construct a *circa* £20 billion 3,200 MWe nuclear power plant at Sizewell C comprising two EPR reactors.

Importantly (given cost implications of attempts to mitigate future climate impact on nuclear power plants), BEIS' recent UK Energy White Paper suggests that HMG remains open to nuclear projects only if significant reductions in costs are possible, along with delivery to time and budget⁸⁴ – noting that industry should deliver the ambitious goal it set itself, (published in HMG's 2018 Nuclear Sector Deal) to reduce the cost of nuclear new-build projects by 30% by 2030.⁸⁵

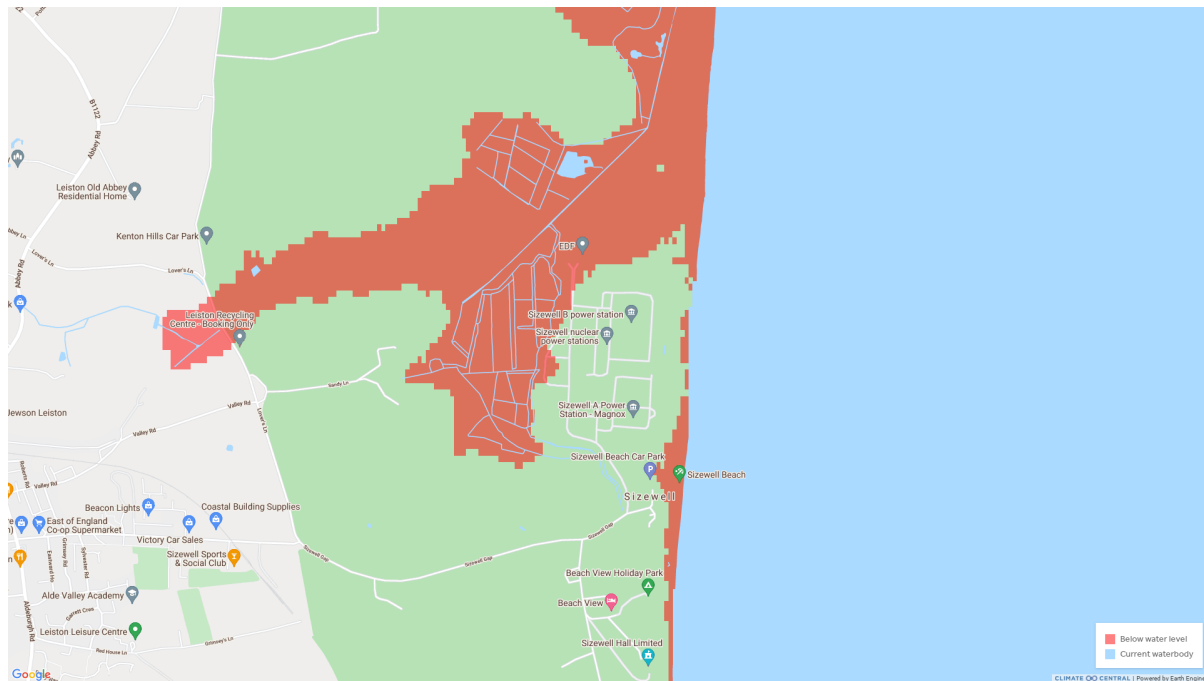
⁸³ Sharma A. & UK Dept. Business Energy & Industrial Strategy (BEIS) (2020): Government sets out plans for clean energy system and green jobs boom to build back greener, Press release, Dec 2020. <https://www.gov.uk/government/news/government-sets-out-plans-for-clean-energy-system-and-green-jobs-boom-to-build-back-greener>

⁸⁴ UK Department for Business, Energy & Industrial Strategy (BEIS) (2020): Energy white paper: Powering our net zero future, CP337, BEIS, Dec 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

⁸⁵ UK Department for Business, Energy & Industrial Strategy (BEIS) (2020): Nuclear Sector Deal: A sector deal between government and the nuclear industry. Policy paper, BEIS, June 2018. <https://www.gov.uk/government/publications/nuclear-sector-deal>

However, this necessary cost-limitation may prove a bridge too far, since any adaptation efforts to mitigate annual flooding (projected to almost entirely surround the proposed EDF Sizewell C EPR nuclear island by 2050) will inevitably entail significantly increased expense for construction, operation, spent nuclear fuel management, rad-waste storage and eventual decommissioning – See Fig.2.

Fig.2 Proposed EDF EPR Sizewell C Nuclear Power Plant Annual Flood Risk Map 2050⁸⁶



⁸⁶ Annual flood level: Water level at shoreline that local coastal floods exceed on average at least once per year at 2050. Emissions pathway: Moderate emissions cuts (RCP 4.5) consistent with the Paris Climate Agreement 2°C target, median climate sensitivity. Elevation model: CoastalDEM.

4.3 The Detail

Radiation protection is not a zero-sum game, rather a considered balancing of opportunities and risks – something greater than the sum of its parts. And as with all projections these maps are models, albeit dependent on conservative scoping assumptions. That said, although these coastal flood maps are based on measured local sea surface and local sea-level rise forecasts (plus the height above sea-level of defined local flood types) – since they are not based on physical storm and flood simulations, risk from actual extreme flood events may be far greater. This is because factors such as erosion, future change in storm intensity and frequency, storm surge, inland flooding and contributions from rainfall or rivers, are not taken into account. In other words, the flood risk projection maps may prove to be an underestimation.⁸⁷ All the more since, in estimating the height of local annual floods above sea-level, this analysis deploys a global model that conservatively estimates potential flood height.⁸⁸

⁸⁷ Kulp S.A. & Strauss B.H. (2019): New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat Commun* 10, 4844, 2019. <https://doi.org/10.1038/s41467-019-12808-z>

⁸⁸ Muis S., et al. (2016): A global reanalysis of storm surges and extreme sea levels. *Nature Commun.* 7:11969 doi: 10.1038/ncomms11969 | 2016.

5. Findings

In the last year, climate models have run hot. As knowledge of enhanced climate sensitivity and polar ice melt rate evolves it's become clear that sea-level rise is significantly faster than previously thought, resulting in more frequent and destructive storm, storm surge, severe precipitation and flooding. As extreme events today become the norm in the future, alteration in storm patterns, storm surge, and river flow will significantly increase 'combined hazards'.

Ramping change in ice dynamics mean that recent observations of sea-level rise significantly exceed projections made only a decade earlier. This rise in sea-level will substantially increase flooding and erosion in coastal areas, particularly when storm surge coincides with normal high tide. And inland climate-driven inundation and flooding is set to become both more frequent and severe. Meanwhile, predicted changes to storm patterns (affecting both storm surge and river flow) will accelerate 'combined hazard' impact, making current risk mitigation measures potentially obsolete.

The corollary to this analysis is that present and planned UK coastal nuclear infrastructure will be at significant and increasing risk from climate impact, vulnerable to sea-level rise, greater storm intensity and storm surge, increasing rainfall, raised river flow, inundation and flooding hazard – fundamentally bringing into question nuclear safety, security and operational viability. In other words, UK nuclear infrastructure is, quite literally, at the front-line of climate change risk.

Integrating very recent peer-reviewed scientific knowledge on climate change impact, this Report's key finding is that UK civil nuclear infrastructure is profoundly unprepared for climate impact and there is a very high probability that reactors and associated high-level spent fuel stores will become unfit for purpose, and soon.

Paradoxically, whilst planned nuclear expansion seeks to provide enhanced energy security, there is a high probability that it will produce the obverse – as the form and function of a planned component of our electricity infrastructure becomes unviable due to ramping climate impact.

This is because risks to nuclear installations from sea-level rise and extreme climate events will not be linear – as there will be thresholds at which existing natural and built barriers are exceeded as storm surge and precipitation intensity increasingly erodes coastal and inland nuclear infrastructure flood defences. The implication being that nuclear industry and ONR efforts to mitigate climate risk will involve very significantly increased expense for any nuclear construction, operation, waste management, decommissioning, and even relocation or abandonment.

6. What to Do

The key 'take-way' from this report implies a substantive reassessment of nuclear's role in UK net-zero.

In other words, nuclear's lower-carbon electricity USP sits in the context of the much larger picture – that UK coastal nuclear will be one of the first, and most significant, casualties to ramping climate impact.

Nuclear is, quite literally, on the front-line of climate change – and not in a good way.

The unfortunate reality is that nuclear, far from helping with our shared climate problem, will add to it – as UK coastal nuclear becomes subject to significant sea-level rise, storm surge and flooding.

All this means that evolutionary modelled prediction of seasonal, decadal, and future climate change impact on UK nuclear infrastructure must be accounted for, including the potential for rapid change extreme events, abrupt interactions and feedbacks.

Further comprehensive nuclear industry and ONR risk assessments based on 'all case' scenarios must be published and regularly updated as fundamental scientific climate impact evidence evolves.

Such an approach must include costings for any necessary mitigation measures and a range of contingency plans for the swift onset of climate-driven severe weather.

In this sense, action on climate change impact on UK nuclear infrastructure should be informed by and flow from UK presidency of COP 26⁸⁹ and the forthcoming Environment Bill,⁹⁰ thereby reinforcing UK Fusion Doctrine.⁹¹

⁸⁹ HM Government (2021): COP 26, HM Govt. 2021. <https://www.gov.uk/government/topical-events/cop26>

⁹⁰ HM Govt (2021): The Queens Speech, HM Govt. 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/985029/Queen_s_Speech_2021_-_Background_Briefing_Notes..pdf

⁹¹ HMG Government (2018): National Security Capability Review: Including the second annual report on implementation of the National Security Strategy and Strategic Defence and Security Review 2015, HMG, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/705347/6.4391_CO_National-Security-Review_web.pdf

Climate Change UK Nuclear, June 2021
Dr Paul Dorfman, Nuclear Consulting Group