European Nuclear Climate Impact

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The NCG, launched in 2007, is an international independent non-profit virtual institute dedicated to providing evidence-based expert research and analysis of nuclear issues. Through publications and scholarly exchanges the NCG seeks to encourage thoughtful debate and inform people and policy about this critical power arena.

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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, raised river flow, 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 coastal and inland nuclear installations will be at significant risk. In other words, nuclear's sustainable electricity claim sits in the context of a much larger picture - that coastal and inland nuclear infrastructure will be some of the first, and most significant, casualties to ramping climate impact.

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

Due to ramping climate induced sea-level rise, storm, storm surge, severe precipitation and raised river-flow, nuclear installations are set to flood - and sooner than either the nuclear industry or regulators suggest. This is because risks to nuclear 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.

Hence, nuclear industry and regulatory efforts to mitigate climate risk will involve significantly increased and unsustainable expense for any nuclear construction, operation, waste management, decommissioning, and even relocation or abandonment. In this sense, 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.

Further, comprehensive regulatory 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.

Thus, nuclear's sustainability claim sits in the context of a much larger picture: That both coastal and inland nuclear infrastructure will be one of the first and most significant casualties to ramping climate impact - strongly implying that new nuclear should not be included in the European Commission sustainable finance Taxonomy.

1. Introduction

The European Commission (EC) has published the rules for sustainable finance, known as the EU Taxonomy, intending to identify economic activities that can be considered economically and environmentally sustainable. The Taxonomy Objectives include: Climate change mitigation, Climate change adaptation, Sustainable use and protection of water and marine resources, Circular economy, Pollution prevention and control, & Biodiversity.

As part of this, the EU Taxonomy Technical Expert Group (TEG) delivered their final recommendations to the Commission; excluding nuclear from the Sustainable Finance Taxonomy 'at this stage', stating that 'it was not possible to conclude the nuclear energy value chain does not cause significant harm to other environmental objectives on the time scales in question'.

Subsequently, the Joint Research Council (JRC) published their assessment of the TEG recommendations, which was handed over to EC's department for financial stability and capital markets (DG FISMA). Meanwhile the JRC report is in the process of being reviewed by two additional expert groups – the first dealing with radiation protection and waste management under Article 31 of the Euratom Treaty, and the second dealing with environmental impacts via the Scientific Committee on Health, Environmental and Emerging Risks.

However, there remains a question as to whether the JRC review has adequately addressed the key concern of climate impact on pan-EU nuclear. In this context, an important issue remains to be resolved: Does nuclear energy pass the Taxonomy's 'Do No Significant Harm' principle in climate protection?

In response, this short report sets recent evolving knowledge about climate impact in the context of pan-EU nuclear power plant flood risk

1.1 Polar Ice-Cap Melt

As the world heats, ice stored at the poles and in glaciers melt and sea levels rise. The rate of rise has accelerated in recent decades and is now estimated at 3 to 4mm a year.[1] 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.[2]

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

[1] 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

[2] 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

out by the Intergovernmental Panel on Climate Change (IPCC).[3] 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.[4],[5]

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.[6]

Here, it is unsettling to reflect that Greenland ice is melting faster than at any time in the past 12,000 years,[7] shrinking by 532 billion tonnes last year, as its surface melts and glaciers fall into the ocean at a rate of seven Olympic-sized swimming pools per second[8] - at a melt-rate matching any in the geological record for the Holocene (the period since the last Quaternary Ice Age).[9]

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

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[3] 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. Pörtner, 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/

[4] 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

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

[6] 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

[7] 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

[8] 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

[9] Briner J.P., Cuzzone J.K., Badgeley 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

Ice Sheet is on the brink of a tipping point, after which accelerated melting would become inevitable.[10]

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.[11]

It is 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.[12] New data from the Antarctic Blue Ice Feild has found that the West Antarctic Ice Sheet has proven unstable during the last warm period (120,000 years ago),[13] and it is 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.[14]

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 1990s[15] - a rate of loss in line with worst-case IPCC scenarios.[16]

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[10] 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

[11] 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

[12] 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

[13] 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.

[14] 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/

[15] 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.

[16] 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/

Put simply, current fundamental scientific knowledge of climate sensitivity and polar ice melt suggests that sea-level rise is significantly faster than previously believed and may exceed up to 2.5 metres within the 21st century.[17]

1.2 Climate Models Run Hot

The U.N.'s World Meteorological Organization (WMO) have very recently reported that rising global temperatures have brought the world 'inexorably closer' to a climate tipping point,[18] noting that there is now a 40% chance that global temperatures will temporarily reach 1.5 degrees Celsius above pre-industrial levels in the next five years - and these odds are rising.[19]

Evolving knowledge based on significantly improved models of coastal sea-level elevations provide new best estimates of climate impact vulnerability,[20] and although model uncertainty is a key challenge,[21] 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 in question.[22]

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.[23]

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[17] 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

[18] World Meteorological Organization (WMO) (2021): Global Annual to Decadal Climate Update, Target years: 2021 and 2021-2025, WMO, 2021. https://hadleyserver.metoffice.gov.uk/wmolc/WMO_GADCU_2020.pdf

[19] Januta A. (2021): Rising global temperatures 'inexorably closer' to climate tipping point - U.N., Reuters, 2021. https://www.reuters.com/business/environment/rising-global-temperatures-inexorably-closer-climate-tipping-point-un-2021-05-27/

[20] 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

[21] 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.

[22] 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

[23] Intergovernmental Panel on Climate Change (IPPC) (2020): AR6 Climate Change 2021: Impacts, Adaptation and VulnerabilityThe Working Group II contribution to the Sixth Assessment Report. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

It is 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.[24] 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.[25]

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.[26]

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 EU should be preparing for its seas, estuaries and tidal rivers to rise by up to 2 metres in the next 80 years.[27] Perhaps disconcertingly, the Delta report adds that the more rapid melting of Antarctic ice sheets have not 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 may be rising faster than IPCC worse-case forecasts.[28]

Meanwhile the world's oceans are heating, reaching their hottest level in recorded history, supercharging the extreme weather impacts of the climate emergency.[29]

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

[25] 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

[26] 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

[27] 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

[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.

[29] Gebbie G. (2021): Combining Modern and Paleoceanographic 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.

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.

1.3 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 is not just the height of the rise in sea-level that is important, it is also the increase in storm surge. As the 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]

High tides cause significant modifications, modulating wave set-up. Yet, although cumulative interactions have significant implications for changes in the frequency

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[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/19e0ccbf8e575a139b7b70a6e875ef8b

[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

and height of future extreme tide and storm surge, climate impact projections are under-rehearsed - including those for 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. Climate Impact

Rising sea levels, modified rainfall patterns and extreme temperatures have been forecast by the European Environment Agency (EEA), with flooding expected to be one of the most prominent climate change risks to people, communities and infrastructure. According to a set of detailed EEA maps which emphasise the scale of climate impact that the EU will face if urgent action is not taken to confront global heating,[37] an upper bound for global mean sea-level rise in the range of up to 2.5 metres will significantly increase coastal flooding.[38]

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.[39]

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.[40] 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 planets sandy beaches by the end of the century in a worst-case scenario that assumes only an 80cm rise in sea-level.[41]

Although these estimates can be set against a forecast of international action on climate breakdown (known as the Representative Concentration Pathway 4.5,[42] where reduced ice-cap melt and lower thermal expansion of water results in only a

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[37] European Environment Agency (EEA) (2020): Climate Change Impacts in Europe, EEA, Feb 2020. https://experience.arcgis.com/experience/5f6596de6c4445a58aec956532b9813d

[38] 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

[39] European Environment Agency (EEA) (2020): *ibid*.

[40] 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

[41] 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

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

50cm sea-level rise by 2100)[43] – to do so seems optimistic, especially considering 'combined hazard' impact.

2.2 Combined Hazard

Sea-level rise and predicted changes to EU storm patterns (affecting storm surge, precipitation and river flow) will alter the probability of multiple hazard events, making previous understanding of risk and mitigation measures potentially 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 and storm precipitation.[44]

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.[45] Meanwhile Inland nuclear power plant faces increasingly severe wildfire, with episodic flooding alternating with low river-flow and raised water temperature - the latter significantly impacting on reactor cooling capacity and, hence, viability.

2.3 Implications

Unfortunately, it seems clear that the low-lying parts of the EU coast, and river basins will be at significant and ramping risk from climate impact - and potentially much sooner than anticipated.

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, greater intensity of inland precipitation and raised river flow (alternating with increasingly severe wildfire, low river-flow and raised water temperature) - inevitably bringing into question the operational safety, security and viability of low-lying coastal and inland nuclear infrastructure.

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[43] 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.

[44] 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

[45] 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

NATO's 2017 Strategic Foresight Analysis has reported that climate change is a 'threat multiplier' involving both coastal and inland regions.[46]

3.1 Beyond Design-Base

Although climate change risk to nuclear power plant seems very great,[47] 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 EU and internationally.[48] 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.[49]

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,[50] efforts to mitigate global heating risk to nuclear will mean significantly increased expense for nuclear construction, operation and decommissioning.[51] Further, since coastal and inland spent fuel

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

[47] 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

[48] 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

[49] 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/

[50] 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

[51] 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

management facilities are vulnerable to unanticipated environmental events,[52] 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.[53] 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 is no question but that nuclear stations are, quite literally, on the front-line of climate change risk.[54]

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,[55] 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.[56] In response, although the U.S Nuclear Energy Agency (NEA) is conducting an as yet unpublished study on nuclear power plant vulnerability to climate change,[57] active protective or adaptation measures remain uncosted and unprioritised.[58]

3.2 Investment, Relocation, Abandonment

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[52] 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#

[53] 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

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[58] 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

Whilst it seems clear that climate change-driven coastal flooding will impact nuclear power stations, the key questions are when and by how much?

The Institute of Mechanical Engineers (IME) state that all existing and proposed new 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'.[59] Perhaps alarmingly, IME point out that coastal nuclear sites will need considerable investment to protect them against rising sea levels, and even relocation or abandonment.[60]

Further, coastal nuclear sites 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.[61]

3.3 Regulatory Uncertainty

Whilst, as discussed, recent evidence strongly suggest that changes in meteorological and coastal flooding hazards from climate change may well prove significant; normal regulation only assess nuclear 'Safety Cases'[62] with the expectation that 'reasonably foreseeable' effects are taken into account. The problem is, even though there will be a significant increase in climate impact events; the definition of what is 'reasonably foreseeable' remains uncertain and largely undefined.

As projections for climate impact contain 'considerable uncertainty', with small changes to storm systems altering the height of storm surges significantly. 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, nuclear power plant owners generally do not have to reconsider their key nuclear safety case in the light of new climate science.

In this context, it is 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

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

[60] 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

[61] 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

[62] 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.

Function model significantly reduces prediction uncertainties.[63] In analysing the results, the research finds that the +1.5°C permanent threshold for dangerous warming will likely be crossed between 2027 - 2042, and all that implies for sea-level rise, storm surge and, hence, current regulation of climate related nuclear risk based on the ‘reasonably foreseeable’ event standard.

[63] 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

4. Findings

Radiation risk is not a zero-sum game, rather a considered balancing of opportunities and risks - something greater than the sum of its parts. 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 coastal 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; with inland climate-driven inundation and flooding set to become 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 coastal and inland 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, 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 pan-EU civil nuclear infrastructure is 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 reasonably soon. Paradoxically, whilst planned nuclear expansion seeks to provide an element of enhanced energy security and a temporary buffer against global warming, there is a high probability that it will produce the obverse - as the form and function of a 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 regulatory efforts to mitigate climate risk will involve very significantly increased expense for any nuclear construction, operation, waste management, decommissioning, and even relocation or abandonment.

5. Recommendations

The key implication from this report is a substantive reassessment of nuclear's role in pan-EU sustainable net-zero. This because nuclear's sustainability claim sits in the context of a much larger picture - that nuclear will be one of the first, and most significant, casualties to ramping climate impact. The unfortunate reality is that nuclear, far from helping with our shared climate problem, may well add to it - as coastal nuclear becomes subject to significant sea-level rise, storm surge and flooding; whilst 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.

The corollary to this analysis is that nuclear should not be included in the European Commission sustainable finance Taxonomy.

In order to monitor and attempt to mitigate ramping climate impact risk to nuclear infrastructure; evolutionary modelled prediction of seasonal, decadal, and future climate change impact on pan-EU nuclear installations must be accounted for, including the potential for rapid change extreme events, abrupt interactions and feedbacks. Further, comprehensive nuclear industry and regulatory 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 precise costings for necessary mitigation measures and a range of contingency plans for the swift onset of climate-driven severe weather.

In this sense, essential precautionary action on climate change impact on nuclear infrastructure should be informed by and flow from the European Green Deal, the EC 2050 Long-Term Strategy, and the Euratom Directives on nuclear safety and on management of spent fuel and radioactive waste.

Dr Paul Dorfman, June 2021.