Why **Climate Robotics**?

Climate Robotics Network White Paper Series 2025

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Autonomous robotic glider captures high-res weather and climate data from 0-to-30-kilometer altitude.

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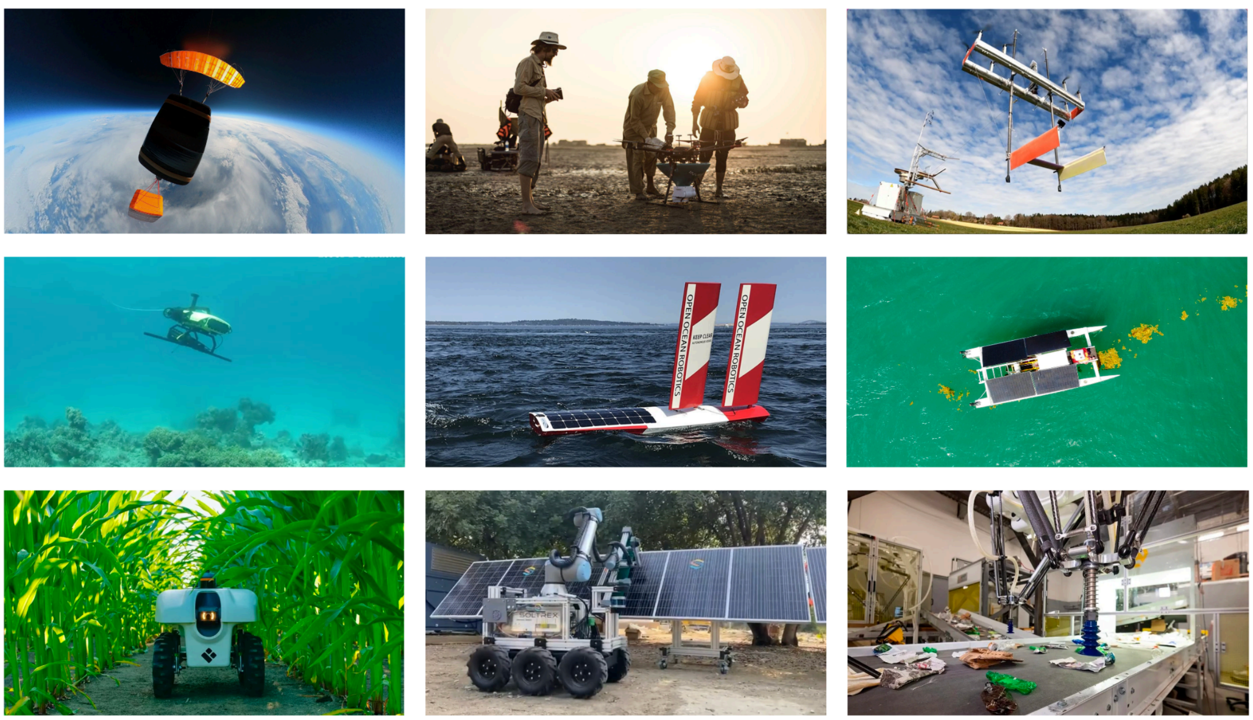
Executive Summary

Climate change is the defining issue of our time. We need all hands, innovative models and appropriate technologies on deck to mitigate the effects of the global emergency and adapt responsibly. For better or worse, we need some level of intelligent automation to scale existing climate solutions and deploy entirely new solutions. The roles of robotics in climate action and climate tech have been largely overlooked, however, hence the launch of the Climate Robotics Network and this exploration on the potential of robotics to scale climate action.

Many sectors and industries use robotics for speed, efficiency, and scale. Robotics can compensate for labor shortages and extend the reach of human abilities. Robotics can also automate tedious, dirty, and dangerous tasks. They can thus serve as a multiplier by enabling the manufacturing, deployment, operations, maintenance and recycling of climate solutions at scale, thereby accelerating the pace and impact of climate action.



Real-world applications of climate robotics include aerial, ocean, and ground robotics, plus robotic arms.

The rapid evolution of Artificial Intelligence (AI) over the past 2 years alone is having a transformative impact on robotics, enabling robots to become more autonomous, intelligent (rapid learning) and interactive in less structured environments. In his keynote address at CES 2025, NVIDIA CEO Jensen Huang charted AI's future trajectory, with Generative AI leading to Agentic AI leading to *Physical AI*, i.e., General-Purpose Robotics. Combining this trend towards Physical AI with the latest advances in soft robotics and bioinspired robotics means that robotics can be deployed for even more climate use-cases, more efficiently and more sustainably.

Still, the new field of Climate Robotics has yet to garner the same level of attention as the application of AI for Climate Action. The World Economic Forum's "Insight Report" on Climate Tech, launched at Davos shows a widespread lack of awareness of robotics' role in Climate Action. This needs to change at all levels, from research to policy to operations.

Our White Paper draws on concrete case studies of climate robotics in action to highlight how existing solutions may augment our capacity to tackle the climate emergency. More specifically, the case studies focus on Restoring Mangroves, Predicting the Weather, Distributing Wind Energy, Regenerating Corals, Collecting Ocean Data, Removing Carbon with Seaweed, Scaling Cover Crop Seeding, Automating Solar Panel Cleaning, and Expanding the Amount of Recycled Waste. These case studies yield essential insights on using robotics in climate action. These include insights on Scaling, Adaptation vs. Mitigation, Bits vs. Atoms, Mobile vs. Fixed Robotics, and Sudden vs. Slow Onset Disasters.

Scaling Climate Solutions. Many of the climate solutions available today are being manufactured, deployed, operated, maintained, disassembled, and recycled manually, which will never scale. Examples include mangrove planting, nature-based carbon removal, and the inspection of green energy infrastructure. In contrast, the above case studies show that robotics can accelerate the deployment of existing climate solutions by automating the circular economy or life cycle of existing and future climate technologies. While some robotics solutions may still be years from reality, many are already being deployed today.

Adaptation and Mitigation. Most of the climate robotics use cases listed above fall into the mitigation category except three: coastal restoration, weather prediction and coral regeneration (which are applications to both adaptation and mitigation). Does this skewed pattern towards mitigation hold if we expand the number of case studies beyond ten (N = 10)? This is an essential question that the Climate Robotics Network is actively researching through its Global Map of Climate Robotics. The map, which already includes well over 250 entries, seeks to document who is doing what, where, how, and why in the Climate Robotics space.

Bits vs. Atoms. While some robotics technologies focus on data collection (i.e., bits), others focus on moving matter (atoms). In some cases, robotics technologies do both explicitly. While robots can both sense (collect data) and shape their environment (physical manipulation), the latter is often overlooked as a central value-add of robotics, mostly because of the inherent complexity in handling the physical interactions. There needs to be more awareness on the role of robotics in climate action when it comes to interacting and changing our environment physically, e.g., by using aerial robots (drones) to plant mangrove seeds, which necessarily changes the coastal environment. It is also worth noting that all autonomous robotics solutions use AI, but not all AI solutions include robotics.

Mobile vs. Fixed. The following categories of robotics appear in the above case studies: aerial, ocean, and ground robotics, as well as robotic arms. The first three in this list are often described as mobile robotics, a core field of robotics. These types of robotics solutions physically move across the spaces we humans occupy and go well beyond them, e.g., to the depths of the oceans and the heights of the stratosphere. These robots often operate in unstructured and dynamic environments, which pose complex challenges to the roboticists. In contrast, robotic (industrial) arms are often fixed at a facility (e.g. waste sorting robots), operate in more structured environments but are expected to be fast and more accurate. That said, several aerial, ocean and ground robots also make use of robotic arms, while others can operate both on land and in the air.

Slow vs. Sudden Onset Disasters. The climate crisis is a planetary-wide emergency that increases the frequency and magnitude of extreme weather events and climate-related disasters. The case studies reviewed here suggest that Climate robotics solutions are being deployed predominantly in response to slow-onset disasters like deforestation, biodiversity loss, pollution, warming oceans, and waste. We need to learn from the Humanitarian Robotics community about how to respond to emergencies at a genuinely planetary scale.

Using robotics in Climate Action also presents many challenges and risks, including **Top-Down Approaches, Techno-Centric Thinking, Lack of Evidence and Accountability, Financing and Affordability, Safety, Privacy and Governance, Simplicity, Maintenance, Repairability, Sustainability, and last but certainly not least, Environmental Impact.**

We unpack and discuss these challenges in detail and note that many are not inherent to robotics alone. The Humanitarian Tech space has faced several challenges, which means best practices and lessons learned already exist to manage these challenges. The Climate Robotics Network is actively drawing on these and other insights to inform the responsible, sustainable, and effective use of robotics in Climate Action. Still, we face far more questions than answers in this new space; hence the need for a climate robotics network, conceptual framework, research agenda, series of white papers, summit, and knowledge base. Some of the leading questions we seek to address as a community include:

Uses Cases

- Which climate solutions are best scaled with robotics?
- What novel solutions can robotics bring to Climate Action?
- What are the cases that applying robotics would do more harm than good?
- What are the early deployment best practices and lessons learned?

Inclusion and Impact

- How do we enable inclusion in the design and deployment of climate robotics?
- How do we ensure diversity, equity, and inclusion in climate robotics?

- Can robotics have a greater impact on climate adaptation or mitigation?
- How do we expand the space for locally-led action in climate robotics?

Enabling Environment

- How do we incentivize the development of simple, low-cost solutions?
- What advances in robotics are essential for Climate Action?
- What are the different funding instruments needed to finance climate robotics solutions?
- What are the skillsets and correct team composition for effective Climate Robotics?

Challenges

- What are the risks and dangers of deploying climate robotics?
- What does ethical, responsible, and sustainable climate robotics look like?
- What existing/future barriers might prevent meaningful progress in climate robotics?
- How do we promote effective dialogue between climate experts and roboticists?
- What policy changes are necessary to enable responsible innovation?

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Why Climate Robotics?

The climate crisis is the defining issue of our time. We need all hands, innovative models and appropriate technologies on deck to mitigate the effects of the emergency and adapt responsibly. We're several trillion dollars short of where we need to be to tackle the crisis.[1] Adaptation finance is less than 10% of overall climate finance.[2] The number of climate migrants and refugees may well cross 200 million before 2050.[3] Already, certain parts of the world are becoming too hot for humans to work outdoors.[4] Many sectors, including agriculture and tourism, are in jeopardy.[5] Renewable energy projects are estimated to create tens of millions of jobs in the coming years, but we don't have the talent for it yet.[6] Each year, so much more is invested in projects that destroy nature than projects that benefit nature.[7] Weather patterns are already changing in ways that make some prediction models inaccurate, including ones powered by Artificial Intelligence (AI).[8] There will also be an enormous need to deploy, operate, maintain and recycle climate technologies, which will be impossible to do manually.[9]

We make these points not because we believe in "doomsday-ism," quite on the contrary.[10] We make these points to build the case for *Climate Action "Plan B"*. Given the current pace of action and the slow political process, climate action without automation is highly unlikely to succeed. Plan B must include appropriate technologies that scale existing climate solutions and/or create new scalable solutions.

Our white paper thus explores the potential of robotics to (1) scale existing solutions and (2) offer novel solutions. We draw on concrete examples of climate robotics to highlight how existing solutions may augment our capacity to tackle the climate emergency. The evidence collected thus far suggests that robotics can serve as a multiplier for climate action. They can accelerate the pace of climate action by expanding our abilities to mitigate and adapt to climate risk.

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1 Staff, M.C. (2022) *How much money is needed to solve climate change?: Aspiration*, *Make Change - Where Money and Mission Meet*. Available at: https://makechange.aspiration.com/how-much-money-to-help-climate-change (Accessed: 16 January 2024). See also: Herweijer, D. and Barry O'Byrne. "Why Climate Tech Desperately Needs More Financial Backing." *World Economic Forum*, 12 Jan. 2024, www.weforum.org/agenda/2024/01/why-climate-tech-desperately-needs-more-financial-backing (Accessed 21 Jan. 2024).

2 *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).

3 Lustgarten, A. (2020) *Where will everyone go?*, *ProPublica*. Available at: https://features.propublica.org/climate-migration/model-how-climate-refugees-move-across-continents (Accessed: 16 January 2024).

4 *Too hot to handle: How climate change may make some places too hot to live*. Available at: https://climate.nasa.gov/explore/ask-nasa-climate/3151/too-hot-to-handle-how-climate-change-may-make-some-places-too-hot-to-live (Accessed: 16 January 2024).

5 Gashler, K. "Report: Warmer Planet Will Trigger Increased Farm Losses." *Phys.org*, 18 Jan. 2024, phys.org/news/2024-01-warmer-planet-trigger-farm-losses.html (Accessed 21 Jan. 2024).

6 *Workers lack the skills for the transition to a green economy - axios*. Available at: https://www.axios.com/2022/02/23/green-talent-jobs-workers-lack-skills (Accessed: 16 January 2024).

7 https://www.earth.com/news/7-trillion-invested-every-year-in-products-and-activities-that-directly-harm-nature

8 Harvey, C. and News, E. (2023) *Climate change could stump AI weather prediction*, *Scientific American*. Available at: https://www.scientificamerican.com/article/climate-change-could-stump-ai-weather-prediction (Accessed: 16 January 2024).

9 Kapoor, J. (2024) *Climate automation: Dirty jobs and a warming planet*, *LinkedIn*. Available at: https://www.linkedin.com/pulse/climate-automation-dirty-jobs-warming-planet-jay-kapoor-hdyle (Accessed: 15 January 2024).

10 https://www.ucdavis.edu/climate/blog/why-climate-doomsday-ism-doesnt-work

Many sectors and industries turn to robots for this multiplier effect, for the speed, efficiency, and scale they offer. This includes automating tasks that are dull (highly tedious and repetitive), dirty (think waste management),[11] and dangerous.[12] As this white paper will show, robotics can accelerate and scale the manufacturing, deployment, operations, maintenance, disassembly and recycling of existing and future climate technologies. In addition, robotics can offer novel solutions for climate action. Robots can also compensate for labor shortages which are becoming serious impediments for climate action across multiple industries in certain regions. While hundreds of billions of dollars are going into reducing emissions and decarbonizing heavy industry, "none of these incentives will matter if we lack a workforce capable of actualizing these changes."[13] Hence, the growing interest in robotics vis-a-vis the United Nations' Sustainable Development Goals (SDGs) more broadly, and climate robotics more specifically.[14]

While some industries suffer from labor shortages, we should also note that robotics and AI technologies pose risks of unemployment, especially for the underprivileged communities and workers without a college degree.[15] In addition, even when the intention of a robotics technology is to automate dull, dirty, and dangerous tasks, there are examples of robotics and AI solutions demeaning jobs or automating only the "cleaner" and "safer" part of a dirty and dangerous task (e.g. recycling robots automating the secondary sorting stage rather than much messier pre-sorting tasks).[16] Therefore, we acknowledge that the labor implications of Climate Robotics can be complex and needs to be a major part of the discussion to provide equitable, community-focused solutions. Indeed, workforce (re)training programs would need to be an essential part of the developed solutions, requiring the governments to take initiative in the education front.[17]

The rapid evolution of Artificial Intelligence (AI) over the past 2 years alone is having a transformative impact on robotics, enabling robots to become more autonomous, intelligent (rapid learning) and interactive in less structured environments. In his keynote address at CES 2025, NVIDIA CEO Jensen Huang charted AI's future trajectory, with Generative AI leading to Agentic AI leading to *Physical AI*, i.e., General-Purpose Robotics. Combining this trend towards Physical AI with the latest advances in soft robotics and bioinspired robotics means that robotics can be deployed for even more climate use-cases, more efficiently and more sustainably.

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[11] Lamb, R. (2023) *10 robots with dirty jobs*, *HowStuffWorks Science*. Available at: https://science.howstuffworks.com/10-robots-with-dirty-jobs.htm (Accessed: 15 January 2024).

[12] For example, dangers around farming: Harrison, D. (2024) *Dying in the fields as temperatures soar*, *Inside Climate News*. Available at: https://insideclimatenews.org/news/31122023/california-farmworkers-dying-in-the-heat (Accessed: 15 January 2024).

[13] Kapoor, J. (2024) *Climate automation: Dirty jobs and a warming planet*, *LinkedIn*. Available at: https://www.linkedin.com/pulse/climate-automation-dirty-jobs-warming-planet-jay-kapoor-hdyle (Accessed: 15 January 2024).

[14] Haidegger, T., et al. "Robotics: Enabler and Inhibitor of the Sustainable Development Goals." *Sustainable Production and Consumption*, vol. 43, 1 Dec. 2023, pp. 422–434, www.sciencedirect.com/science/article/pii/S2352550923002634 (Accessed 20 January 2024).

[15] Acemoglu, D. and Restrepo, P., 2024. Automation and Rent Dissipation: Implications for Wages, Inequality, and Productivity (No. w32536). National Bureau of Economic Research.

[16] Jiang, W. Y., & Wrzesniewski, A. (2023). Perceiving Fixed or Flexible Meaning: Toward a Model of Meaning Fixedness and Navigating Occupational Destabilization. Administrative Science Quarterly, 68(4), 1008-1055. https://doi.org/10.1177/00018392231196062 (Accessed 10 January 2025); Bourmault N., Anteby M. 2020 "Unpacking the managerial blues: How expectations formed in the past carry into new jobs." Organization Science, 31: 1452–1474.

[17] Goldin, Claudia Dale and Lawrence F Katz (2008): The Race Between Education and Technology, Harvard University Press Cambridge.

In short, robotics is a transformational technology that extends the reach of our human abilities, from collecting high-solution data in extreme environments to physically reshaping our environment.[18] That said, the new field of Climate Robotics hasn't garnered the same level of attention as the application of Artificial Intelligence (AI) for Climate Action. The reason is simple: widespread lack of awareness. Take the World Economic Forum's (WEF) new "Insight Report" on Climate Tech, which launched at Davos in January 2024.[19] The words "robot," "robotics," and "automation" do not appear in the 49-page report. Granted, there are six short paragraphs on using drones, albeit for data collection and search-and-rescue. This general lack of awareness needs to change at *all* levels, which is another reason for this White Paper.

But what do we mean by "Climate Robotics"? We first need to understand the scope of what climate robotics entails to fully answer the question, "Why Climate Robotics?" We could launch into abstract definitions. But we prefer to begin with concrete, real-world examples and, from there, return to the question "Why Climate Robotics?" and "How?" That is, how best to research, design, deploy, and evaluate climate robotics.

Based on the early answers we've found to these questions—via the applied research for this White Paper, the Global Map of Climate Robotics[20] and the first-ever Climate Robotics Summit held in May 2024[21]—we can already make the case that robotics has a role to play in supporting climate tech. To be fair, we had an inkling that this would be the case, which is why we launched the Climate Robotics Network in early 2023:[22] to better understand the roles, limitations, challenges, and risks of deploying robotics for climate action and facilitate opportunities and foster collaborations among the community. We address each of these dimensions in the paper. The Network is also developing a Code of Conduct and recently launched a video series on "Climate Robotics in Action." We discuss these and other Network activities in more detail below.

In sum, this white paper seeks to develop a conceptual framework to critically assess the opportunities, challenges, and risks around applying robotics to climate action.

[18] Haidegger, T., et al. "Robotics: Enabler and Inhibitor of the Sustainable Development Goals." *Sustainable Production and Consumption*, vol. 43, 1 Dec. 2023, pp. 422–434, www.sciencedirect.com/science/article/pii/S2352550923002634 (Accessed 20 January 2024).

[19] *Innovation and Adaptation in the Climate Crisis: Technology for the New Normal. World Economic Forum. Insight Report, January 2024.* Available at: https://www3.weforum.org/docs/WEF_Innovation_and_Adaptation_in_the_Climate_Crisis_2024.pdf (Accessed: 17 January 2024).

[20] Resources available at the Climate Robotics Summit: https://climaterobotics.network/resources

[21] Climate Robotics Summit: https://climaterobotics.network/summit

[22] To learn more and join the open network, please join us on Slack: climaterobotics.network.

What is Climate Robotics?

"Climate Robotics" is a subset of Climate Technology, and Climate Tech is defined as technology "built with the intent to mitigate or adapt to the negative impacts of climate change."[23] As such, "Climate Robotics" encompasses the use of robotics intended to address urgent climate change and sustainability challenges. Unlike "Environmental Robotics," for example, the sense of urgency and focusing effect of "climate" may be a defining trait of climate robotics. Every one of us is affected by the climate.

That said, unlike the standard definition of Climate Tech, we believe that the new field of "Climate Robotics" must also include robotics solutions that were *not* initially intended to tackle climate-related problems. The inherent capabilities of these (unintended) climate robotics solutions may still be effective in responding to the urgent and intricate issues posed by the climate crisis. So, "Who is a climate roboticist?" We find this question problematic because we strongly believe that the field of climate robotics must be inclusive and massively multi-disciplinary to be effective.[24] Taking a tech-centric approach to climate robotics is not only bound to result in failure, but also to cause harm. As such, if you identify as being part of the "Climate Robotics" community, then that's more than enough, regardless of your background and experience.

This leads us to the following question: how is Climate Robotics practically applied to address these challenges? The Climate Robotics Network's Global Map of Climate Robotics has identified some 250 startups and companies developing, testing, and/or deploying robotics solutions to scale climate action. This section draws on this Global Map to present concrete examples of climate robotics in action. The examples below illustrate what may be possible in the climate robotics space. More specifically, the case studies focus on Restoring Mangroves, Predicting the Weather, Distributing Wind Energy, Regenerating Corals, Collecting Ocean Data, Removing Carbon with Seaweed, Scaling Cover Crop Seeding, Automating Solar Panel Cleaning, and Expanding the Amount of Recycled Waste.

These cases were selected from the Global Map to cover a relatively broad range of climate verticals to show that robotics stands to play several supporting roles in the climate action space. For every company featured below, many others are engaged in scaling the same or similar climate solutions, whether that be in the context of manufacturing, deploying, operating, maintaining or recycling said solutions.

To be clear, we're *not* highlighting these cases because of their impact to date but to invite an informed discussion on the potential applications of robotics for climate action. We haven't tested the solutions below or independently assessed their impact (yet). Nor have we analyzed the business models, market opportunities or go-to-market strategies of the startups/companies behind these technologies. We know that robotics has more than its share of well-intentioned startups trying to solve important problems,

[23] *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).
[24] *Dr. Victoria Preston, conference call on June 20, 2024.*

only to realize that there is no way to run a sustainable business doing so. Nevertheless, we believe that this array of solutions provide an inspiring discussion ground, allowing us to elaborate on the wide span and huge potential impact of climate robotics.

In sum, the section below, like the White Paper, discusses specific opportunities, limitations, and risks vis-à-vis the use of robotics in climate robotics. We believe this open and collaborative approach is key to tackling the challenges ahead, including hurdles related to business models and market opportunities. We also believe that documenting examples of climate robotics solutions that make *no* sense is equally important. As such, this will be the topic of a future paper in this series.[25]

[25] Take the following pilot project, for example, which tested the use of robotic arms for the purposes of seeding plants in the Peruvian Amazon Rainforest: Patrick Meier, P. (2024) *Patrick Meier, PhD on LinkedIn.* Available at: https://www.linkedin.com/posts/meierpatrick_climate-robotics-climatetech-activity-7151262522849861633-cJMk (Accessed: 15 January 2024).

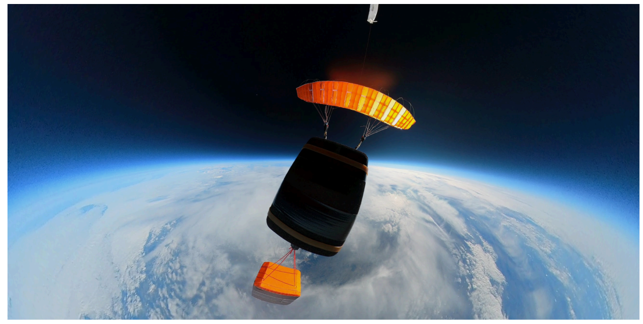

Restoring Mangroves, Climate Superheroes

Mangroves are tropical plants adapted to loose, wet soils and salt water and periodically submerged by tides. Mangroves, compared to tropical upland forests, can store up to 5 times more organic carbon.[26] Unfortunately, historic rates of mangrove deforestation since 1950 have destroyed an estimated 50% of the world's mangroves, primarily due to land-use change.[27] They're also essential to biodiversity, local livelihoods, and coastal protection. We need to rapidly restore mangroves in coast areas globally.[28]

The good news is that many communities worldwide are actively hand-planting new mangroves, and scientists have identified 10,000 km^2 of land across the planet that is perfect for mangrove seedlings.[29] But 10,000 km^2 is the equivalent of half a billion full-size football fields. This could take time, as planting new mangroves by hand is tedious, time-consuming, and expensive.

The startup Inverto Earth and others are thus exploring ways to scale this effort. More specifically, Inverto seeks to scale nature-based solutions by using drones.[30] The young company, which is based in Switzerland, has developed a drone-optimized release mechanism that autonomously releases mangrove seeds from the air (pictured above). The startup has carried out proof-of-concept projects in Pakistan and Abu Dhabi. From this work, Inverto has learned that it takes around 25 individuals a whole day to plant 1 hectare of mangroves in Pakistan, for example. Inverto has demonstrated that combining hand planting with drones can scale mangrove planting to 200 hectares in just one day. Whether drone-released seeds grow into whole, healthy mangroves remains to be seen and may take years to determine.

[26] Donato, D., Kauffman, J., Murdiyarso, D. et al. Mangroves among the most carbon-rich forests in the tropics. Nature Geosci 4, 293–297 (2011). https://doi.org/10.1038/ngeo1123 (Accessed: 17 January 2024)
[27] Alongi, Daniel M. "Present State and Future of the World's Mangrove Forests." Environmental Conservation 29, no. 3 (2002): 331-49. doi:10.1017/S0376892902000231. (Accessed: 17 January 2024)
[28] There's an uptick in activity in the conservation finance space around nature based solutions in general and much of this focuses on mangrove restoration. There is also a lot of activity in general in nature tech investment as well, e.g. Monitoring Reporting and Verification technologies that are directly relevant to mangrove restoration.
[29] Inverto slide deck shared with Patrick Meier in December 2023. It's worth highlighting the fact that there's an uptick in activity in the conservation finance space around nature based solutions in general and much of this focuses on mangrove restoration. There is also a lot of activity in general in nature tech investment as well. Take, for example, Monitoring Reporting and Verification (MVR) technologies that are directly relevant to mangrove restoration.
[30] https://www.inverto.tech. Disclaimer: Lead author Patrick Meier was involved in incubating this startup and served as an advisor.

Weather Prediction

Scientists have recently discovered that subtle changes in the stratosphere can cause and influence these extreme events on the planet's surface.[31] Extreme cold snaps in the northern hemisphere can "occur when the polar vortex in the stratosphere suddenly heats up and collapses—as is happening right now."[32] Other examples include severe storms that "had a direct connection to what was happening in the stratosphere at the time." In addition, scientists have found evidence that the stratosphere played a role in the "extreme forest fires in Australia and mini hurricanes in the Arctic Ocean." However, scientists say they need considerably more data at higher resolutions to make better prediction models. This lack of data continues to result in unreliable long-range forecasts. Expanding the use of weather balloons equipped with radiosondes (sensor packages) won't cut it.

Around 600,000 radiosondes are launched across the planet every year. The balloons pop once they reach a certain altitude, and a small parachute brings the sensors back to the planet's surface. Due to changing winds and weather conditions, these parachutes and sensors rarely land close to their launch sites. This explains why 75% of these parachutes and sensors are never recovered, as doing so is too costly and time-consuming. These one-way flights mean nearly half a million non-biodegradable parachutes, sensors, electronics, and batteries are littering the planet yearly.

The Swiss-based startup *FreeGlide* (based on the R2Home Project) and others are exploring ways to increase the quantity and quality of atmospheric data collection for climate action. More specifically, FreeGlide is developing robotics solutions to collect more frequent, higher resolution weather data at higher altitudes while doing so more cost-efficiently and with a smaller environmental footprint than other solutions.[33] The startup is testing stratospheric robotic gliders that return radiosondes to their launch sites autonomously (pictured above). Their approach makes radiosondes fully reusable and more cost-effective, meaning more radiosondes can be deployed with a smaller environmental footprint. FreeGlide has been testing its technology in partnership with MeteoSuisse since 2022. Whether the team can overcome some technical challenges in deploying their system remains to be seen.

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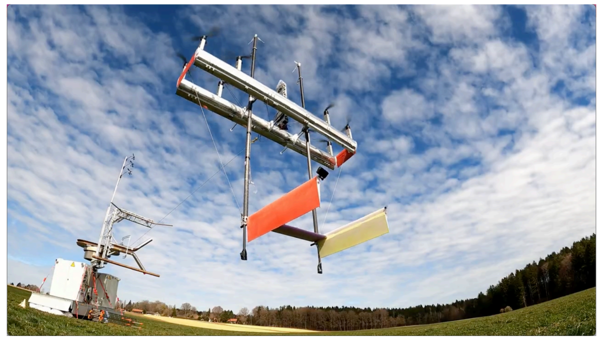
[31] Ruegg, P. (2021) *Extreme weather from the stratosphere*, *Phys.org*. Available at: https://phys.org/news/2021-01-extreme-weather-stratosphere.html (Accessed: 15 January 2024).
[32] This quote, and all others that follow in this paragraph are also taken from Ruegg, P. (2021).
[33] https://www.freeglide.space; Disclaimer: Lead author Patrick Meier formally advised this startup.



Distributed Wind Energy

Billions of new wind turbines are needed to meet global net-zero emission goals.[34] However, traditional turbines often face public opposition due to their visual impact on natural landscapes since many complain that these massive structures ruin the view of nature. Building and deploying these massive structures is also expensive and challenging. Moreover, some startups and companies complain that obtaining regulatory approvals for deploying these turbines often entails a lengthy permitting process. In addition, the world's most windy areas tend to be in very remote locations, which means the electricity needs to be transmitted over long distances.[35] This, in turn, means more electricity loss during the transmission process.[36]

The German startup KiteKraft (and others) is thus exploring ways to scale wind energy generation. In KiteKraft's case, the startup is building "flying wind turbines'' to generate clean energy.[37] The startup is building and testing a tethered drone that glides like a kite at altitude. As is well known, there's far more wind at altitude than at the surface. As this wind enables the drone to glide, it also turns its eight propellers, which act as small wind turbines. The tether connecting the drone to the ground station transmits the electricity to the surface, which can be used immediately.

The startup's drone is barely noticeable when deployed at altitude, so it doesn't cause visual or noise pollution. This enables KiteKraft to operate close to urban centers. Their technology has a smaller environmental footprint as it uses 90% less material than traditional turbines. It is also quicker to deploy. The startup believes that its solution can slash the cost of wind energy by half. Whether KiteKraft can deploy its solution at scale and actively compete with traditional wind turbines is an open question.

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34 *Wind power must gather speed to meet climate goals, report finds* (no date) *euronews*. Available at: https://www.euronews.com/green/2022/04/04/global-wind-power-must-gather-speed-to-meet-climate-goals-report-finds (Accessed: 15 January 2024).

35 *Advantages and challenges of wind energy* (no date) *Energy.gov*. Available at: https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy (Accessed: 15 January 2024).

36 Wirfs-Brock, J. (2017) *Lost in transmission: How much electricity disappears between a power plant and your plug?*, *Inside Energy*. Available at: https://insideenergy.org/2015/11/06/lost-in-transmission-how-much-electricity-disappears-between-a-power-plant-and-your-plug (Accessed: 15 January 2024).

37 https://www.kitekraft.de


Regenerating Corals, the Jewels of the Ocean

Approximately one billion humans around the world depend on coral reefs for their livelihoods.[38] "Globally, coral reefs provide tropical coastal societies with critical economic, livelihood, and food security benefits. Global estimates suggest reefs provide some $375 billion worth of goods and services. Much of this value is derived from support for substantial tourism markets for diving and snorkeling, shoreline protection, and, of course, fisheries."[39] Moreover, these diverse ecosystems house a quarter of all marine life, serving as critical habitats for a wide range of aquatic life. In short, their importance extends beyond ecological diversity, significantly contributing to many communities' economic stability and food security.

One of our favorite facts about corals is the magic they perform once a year. When the full moon is bright, and the temperature of the water is just right, corals release millions of "baby corals." Mother Nature has optimized to release millions of these young corals because only 0.0001% survive and grow into full corals. So, this extremely low survival rate has simply not mattered until now. The climate crisis is hitting corals hard. Scientists warn that 99% of the world's corals will disappear in our lifetime if we don't act now.[40] Thankfully, marine scientists have developed ways to create "coral nurseries" or kindergartens, which significantly increase the survival rate of baby corals. But releasing these back into the big blue Ocean is a manual process requiring a lot of equipment.

Several startups and research programs are thus exploring ways to scale this labor-intensive and time-consuming process. For example, the Queensland University of Technology (QUT) in Australia has developed an underwater robot to spread coral babies by the millions.[41] According to QUT, the underwater robot can cover 21.8 times more area than manual methods and is already deployed in Australia, Vietnam, the Philippines, and the Maldives. It remains to be seen whether this technology can be scaled globally and what the best business model is to make this happen.

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[38] *Why we need coral reefs* (no date) *Great Barrier Reef Foundation*. Available at: https://www.barrierreef.org/news/blog/why-we-need-coral-reefs (Accessed: 15 January 2024).

[39] Author links open overlay panelJoshua Cinner *et al.* (2013) *Coral Reef Livelihoods*, *Current Opinion in Environmental Sustainability*. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1877343513001875 (Accessed: 15 January 2024).

[40] Heron, Scott , et al. "99% of Coral Reefs Could Disappear If We Don't Slash Emissions This Decade, Alarming New Study Shows." *World Economic Forum*, 4 Feb. 2022, www.weforum.org/agenda/2022/02/coral-reefs-extinct-global-warming-new-study (Accessed: 15 January 2024).

[41] Queensland University of Technology. (2023) *Restore the great barrier reef*, *QUT*. Available at: https://www.qut.edu.au/engage/giving/support-research/great-barrier-reef (Accessed: 15 January 2024).

Collecting Ocean Data to Support Climate Action

Ocean data plays an instrumental role in climate adaptation plans. Predicting marine heatwaves, managing ecosystems, and implementing carbon dioxide strategies require high-resolution ocean data. The ocean is a source of enormous potential in mitigating climate change and a frontline witness to its impacts. The need for reliable, timely, and comprehensive ocean data is thus essential.

Collecting this data, however, has typically been slow and challenging, even dangerous. Open ocean surveillance has traditionally been conducted using fixed assets on shore, satellites, crewed ships, or aircraft. These methods are expensive, polluting, lack resolution, and require significant resources and personnel. Moreover, the oceans cover over 70% of the planet, and collecting data across this vast amount of space is a massive undertaking, not least given that data collection needs to go well below the ocean surface alone.

Many startups and companies in ocean robotics are developing solutions to scale the autonomous collection of timely, high-quality ocean data. One such startup is US-based Open Ocean Robotics, which deploys solar-powered ocean robots that collect data from the ocean's surface.[42] These solutions are used to help increase biodiversity in sensitive marine-protected areas, which play a crucial role in carbon sequestration.

The startup also creates monitoring, verification, and reporting solutions (MRV) for carbon sequestration methods, including alkalinity enhancement and macroalgae growth. In addition, they're looking to provide the shipping industry with better data to shorten ship routes. The shipping industry can conserve fuel and reduce emissions by helping ships drive more fuel-efficient routes using real-time information on ocean conditions.

[42] https://www.openoceanrobotics.com

 

Leveraging the Planet's Ultimate Carbon Sink

Scientists have made it clear that oceans are vital to meeting global climate goals.[43] According to one study, moving all of humanity's carbon emissions generated since industrial times to the deep ocean would only add 4% to the ocean's total storage of CO_2.[44] How does one move carbon dioxide to the deep ocean? Well, one way may be seaweed. Indeed, seaweed absorbs as much carbon as the Amazon Rainforest.[45]

Furthermore, sinking carbon-rich seaweed into the deep ocean removes it from the surface carbon cycle for at least 100 years.[46] And it's worth noting that some types of seaweed, like sargassum, can "wreck local economies, ecosystems – and even threaten health" when they accumulate on the ocean surface.[47] So, the real question may actually be whether there's a cost-effective way to grow, collect, and sink seaweed at scale. Besides carbon removal, seaweed offers several critical ecological benefits and can be used as food, fertilizer, animal feed, and packaging.

Several startups like Seaweed Generation are actively exploring this question. Seaweed Generation is building ocean robots to scale carbon reduction and removal.[48] Specifically, the UK startup designs and tests ocean robots to grow, manage, monitor, harvest, transport, and sink seaweed. Ultimately, the idea is for the robots to collect the floating seaweed from the surface and sink the carbon-packed seaweed to the sea floor, where it can be locked away for hundreds of years. The environmental and social risks of doing this at scale remain to be seen. What's required is extensive data collection and close monitoring, which the startup will be doing with oversight from its Scientific Board.

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43 *The ocean – the world's Greatest Ally Against Climate change* (no date) *United Nations*. Available at: https://www.un.org/en/climatechange/science/climate-issues/ocean (Accessed: 16 January 2024).

44 Seaweed Generation (no date) *White Paper: Deep sea carbon storage using macroalgae*, *Seaweed Generation*. Available at: https://www.seaweedgeneration.com/education/2023-11-16-deep-sea-carbon-storage-using-macroalgae.html (Accessed: 16 January 2024).

45 McCoy, M.K. (2023) *New study reveals seaweed's hidden climate benefits*. Available at: https://www.conservation.org/blog/new-study-reveals-seaweed-s-hidden-climate-benefits (Accessed: 16 January 2024).

46 Fujita, R. *et al.* (2022) *Carbon sequestration by seaweed : Background paper for the Bezos Earth Fund - EDF Workshop on seaweed carbon sequestration*, *OceanRep*. Available at: https://oceanrep.geomar.de/id/eprint/57685 (Accessed: 16 January 2024).

47 Olson, E. (2023) *A new robot could help fight climate change by sinking stinky seaweed*, *NPR*. Available at: https://www.npr.org/2023/10/03/1203404507/a-new-robot-could-help-fight-climate-change-by-sinking-stinky-seaweed (Accessed: 15 January 2024).

48 https://www.seaweedgeneration.com


Scaling Cover Crop Seeding

Planting cover crops offers essential benefits in agriculture.[49] A cover crop is a crop that is planted and grown for the protection and enrichment of the soil. Cover crops are planted before/after cash crops have been harvested. To this end, cover crops are plants grown primarily to benefit the successful growth of other crops in the future. One of the best cover crops for aerating compacted soils and improving water infiltration is tillage radish or daikon radish.

Planting cover crops provides multiple benefits, such as controlling erosion, suppressing weeds, reducing soil compaction, increasing moisture and nutrient content of soil, improving yield potential, and attracting pollinators.[50] They're also crucial in helping to sequester carbon. Planting cover crops comes with many challenges, however. This includes increased costs, labor needs, and management oversight. In addition, the time windows for cover crop seeding can be particularly short.

The American startup EarthSense (and others) are exploring ways to decarbonize and scale agriculture. In the case of EarthSense, the startup is developing and deploying a fleet of autonomous ground robots to make farming more efficient and sustainable.[51] One area they focus on is cover crops. The startup's tablet-operated autonomous robot can seed 10 to 15 acres daily by carrying 40 kilos of cover crop seed at a time. The goal of autonomous robot seeding is to get much earlier and more complete germination of the cover crop. Earthsense has demonstrated that using its cover crop interseeding robot can measurably increase early season yields and sequester far more carbon than cover crops seeded using tractors. Whether the startup can convince more farmers to switch to their autonomous solutions remains to be seen.

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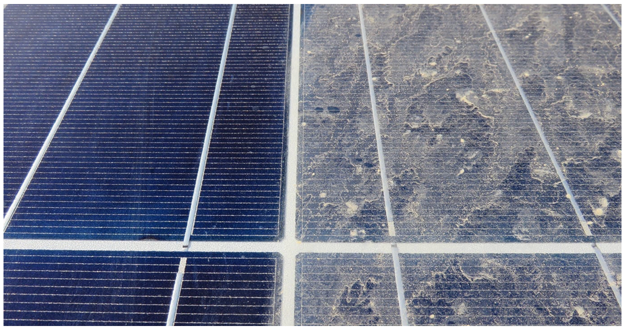
[49] *Benefits of cover crops* (2023) *SARE*. Available at: https://www.sare.org/publications/managing-cover-crops-profitably/benefits-of-cover-crops (Accessed: 16 January 2024).
[50] *Benefits of cover crops* (2023) *SARE*. Available at: https://www.sare.org/publications/managing-cover-crops-profitably/benefits-of-cover-crops (Accessed: 16 January 2024).
[51] https://www.earthsense.co



Automating the Cleaning of Solar Panels

Recent research has shown that dirty panels can lose up to 50% of their efficiency.[52] So they all need to be cleaned, which is typically by hand. This can take a lot of time and a fair amount of water.[53] Imagine cleaning all the panels in the Bhadla Solar Park in India, for example.[54] This solar farm covers over 50 km^2 and uses some 10,000,000 solar panels to generate 732,874 MWh of clean energy annually. It reportedly takes 3-5 liters of water to clean one solar panel, which means it can take up to 50 million liters of water to clean the panels in Bhadla Solar Park once a year.[55] This is enough water to fill 20 Olympic-sized swimming pools. Put differently, 50 million liters of water is enough to keep 50,000 human beings healthy and alive for 365 days. Note that Bhadla Solar Park is located in a vast desert prone to numerous dust storms, which means the panels need to be cleaned multiple times a year.[56]

While some solutions have been developed to speed up the cleaning of solar panels, they still require dedicated human intervention. Solar energy is central to meeting national and global climate goals, meaning billions more solar panels will be built and deployed between now and 2050. Each panel will need to be maintained and cleaned using minimal human intervention.

Soltrex and other startups are exploring ways to automate the cleaning of solar panels. The young company is building and testing ground robots that automatically clean solar panels while reducing or eliminating water use.[57] Also, Soltrex is looking to fit the robot with several sensors to detect degraded and cracked panels, thus providing a timely feedback loop for preventative maintenance and repairs. It remains to be seen just how adaptable this ground robot is to the different layouts of solar farms and the different sizes of solar panels, i.e., how much human intervention is required to accommodate different configurations and sizes.

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52 Hicks, W. (2021) *Solar 'soiling': Energy loss from dust on panels can range from 7% to 50%*, *Energy Post*. Available at: https://energypost.eu/solar-soiling-energy-loss-from-dust-on-panels-can-range-from-7-to-50 (Accessed: 16 January 2024).

53 R. K. Jones, A. Baras, A. Al Saeeri, A. Al Qahtani, A. O. Al Amoudi, Y. Al Shaya, M. Alodan, S. A. Al-Hsaien, Optimized cleaning cost and schedule based on observed soiling conditions for photovoltaic plants in Central Saudi Arabia. IEEE J. Photovoltaics. 6, 730–738 (2016).

54 "Bhadla Solar Park." *Wikipedia*, 22 Mar. 2020, en.wikipedia.org/wiki/Bhadla_Solar_Park (Accessed: 16 January 2024).

55 "Waterless Way: Dry Cleaning Solutions for Solar Panels." *Renewable Watch*, 3 Dec. 2020, renewablewatch.in/2020/12/03/waterless-way (Accessed 18 January 2024).

56 This location was selected for the solar farm because the area gets 300 sunny days per year and barely 10 centimeters in annual rainfall. So the water needs to be transported to the Park from much further away.

57 https://www.linkedin.com/company/soltrex


Expanding the Amount of Recycled Waste

Less than 20% of waste is recycled annually globally. The remaining 80% ends up in landfills and open dump sites.[58] This can lead to harmful chemicals from said waste seeping into the soil, groundwater, and atmosphere. To make matters worse, the amount of waste on the planet is expected to grow by a staggering 70% in the next 30 years.[59] As landfills and other dump sites overflow, they destroy natural habitats. What's more, producing plastic items generates a significant amount of greenhouse gases. Expanding the percentage of waste that is recycled is imperative. However, the recycling process is still expensive and time-consuming.

AMP Robotics and others are exploring ways to automate the sorting of waste. The American startup combines computer vision, artificial intelligence, and robotic arms to recognize and physically sort specific recyclable materials within a complex waste stream of smashed, folded, and tattered objects—all combined.[60] Their AI platform distinguishes between different plastic polymers, paper types, metal containers, and multilayered packages to characterize the recycling stream and what needs to be sorted during different process stages. This data subsequently guides high-speed robotic arms to sort and recover what materials to recycle or remove. The company claims its AI solution recognizes more than 70 billion objects derived from experience and repetition in real-world conditions.

We've documented many more examples and use cases in the Global Map of Climate Robotics, which we don't have the space to cover here. These include the application of robotics in construction, renovation, insulation, roofing, ocean shipping, aviation, and energy transition, for example. Future white papers will dive deeper into these sectors to build our knowledge of the potential of Climate Robotics. We invite interested researchers and prospective co-authors to connect with the Climate Robotics Network to explore the research opportunities available.[61]

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[58] All facts referenced in this section are from: Filipenco, Daniil. "DevelopmentAid." *DevelopmentAid*, 7 Mar. 2023, www.developmentaid.org/news-stream/post/158158/world-waste-statistics-by-country (Accessed: 16 January 2024).
[59] Nandy, Suman, et al. "Green Economy and Waste Management: An Inevitable Plan for Materials Science." *Progress in Natural Science: Materials International*, vol. 32, no. 1, Jan. 2022, https://doi.org/10.1016/j.pnsc.2022.01.001.
[60] https://www.amprobotics.com
[61] Please contact Dr. Patrick Meier, patrick@climaterobotics.network

Insights on Climate Robotics

This section analyzes the use cases and applications described above to illuminate how we might critically discuss and make sense of the climate robotics space. In other words, we can use these mini-case studies to develop an initial conceptual framework for climate robotics, which can shape and inform the discourse, research, deployment, and funding of climate robotics rigorously and responsibly.

The common threads that can be gleaned from the above applications include Scaling, Adaptation vs. Mitigation, Bits vs. Atoms, Mobile vs. Fixed Robotics, and Sudden vs. Slow Onset, for example. We now turn to these threads to gain insights into what they might mean for the new field of climate robotics.

Scaling Climate Solutions

The not-for-profit organization Project Drawdown has developed a Solutions Library with 100 climate solutions categorized by sector area.[62] The nonprofit reviewed each solution based on scientific research and ranked these solutions as a function of carbon dioxide reduction or sequestration.[63] These solutions include Coastal Wetland Restoration, Seaweed Farming, Utility-Scale Photovoltaics, Wind Turbines, Insulation, Building Retrofitting, Improved Aquaculture, Reduced Food Waste, Forest Protection, Conservation Agriculture, Regenerative Annual Cropping, Recycling, Forest and Farmland Restoration, Efficient Aviation and Ocean Shipping, for example.

To this end, when discussing climate robotics, we can zero in on the specific climate solution, i.e., those solutions identified and documented by Project Drawdown. These climate solutions already exist and can thus be used as emergency brakes right now to avoid veering off the climate cliff. As Drawdown's Jonathan Foley likes to say: "Deploy, deploy, deploy!" Immediate action is vitally important, which is why Drawdown is less interested in futuristic technologies, as these cannot serve as the emergency brakes we urgently need. That said, when we say "deploy, deploy, deploy," what often happens is that we "*manually* deploy, deploy, deploy." Manual deployments do not scale.[64] They're slow, labor-intensive, and expensive. This is where robotics can make a difference by scaling the deployment of existing climate solutions; they can "eliminate the bottlenecks that limit their expansion."[65]

Scaling up existing solutions is where robots thrive.[66] Many of the climate robotics applications described in the previous section seek to accelerate the deployment of existing climate solutions, including many already identified by Project Drawdown. How? By accelerating manufacturing, deployments, operations,

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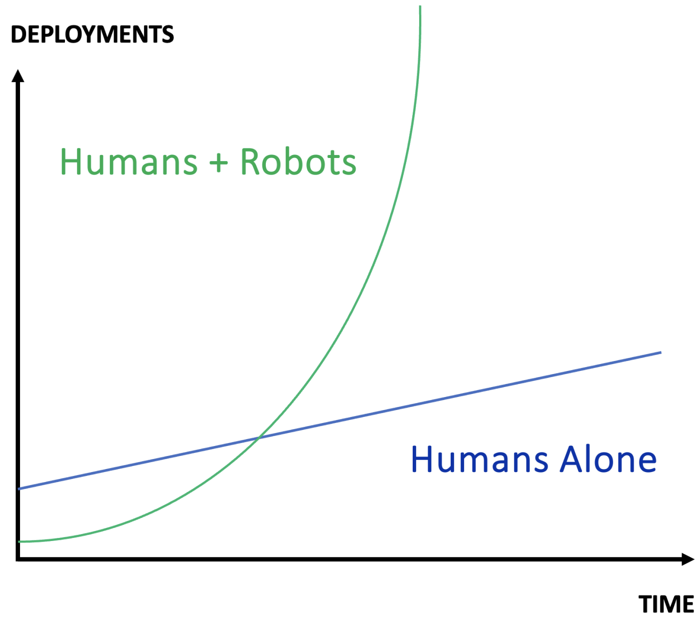
62 *Drawdown Solutions Library* (2023) *Project Drawdown*. Available at: https://drawdown.org/solutions (Accessed: 15 January 2024).
63 It's worth noting that the Solutions Library focuses predominantly on climate mitigation.
64 Romanek, N. (2023) *Your new climate hero has six legs*, *TechInformed*. Available at: https://techinformed.com/your-new-climate-hero-has-six-legs (Accessed: 15 January 2024).
65 Chen, S. (2023) *How roboticists can tackle climate change*, *IEEE Spectrum*. Available at: https://spectrum.ieee.org/robotics-climate-change (Accessed: 15 January 2024).
66 Chen, S. (2023) *How roboticists can tackle climate change*, *IEEE Spectrum*. Available at: https://spectrum.ieee.org/robotics-climate-change (Accessed: 15 January 2024).

maintenance, disassembly and recycling. Moreover, many of these robotics solutions already exist, which means they aren't as futuristic as Nuclear Fusion.[67]

Another value add of robotics is the plummeting costs of this technology. That being said, cost is relative, and access to robotics is far from equal. The following section on challenges will expand on this and other issues.



Naturally, some robotics solutions may still be years from reality. However, some are already being deployed today to accelerate climate action. We need a comprehensive map of the climate robotics space to understand better who is doing what, where, with what types of robots, and why, i.e., to tackle what specific parts of the climate crisis?

Naturally, we must also document and better understand the results of these deployments, especially their lessons learned, successes, and failures.

The urgency of specific climate issues must serve to inform which technologies to prioritize and when to finance them, given the tradeoffs and opportunity costs involved. The Stockholm Resilience Center's Planetary Boundaries Project assesses nine environmental boundaries that should not be crossed as doing so could create irreversible setbacks in our pursuit of sustainable development.[68] As of 2023, six of these boundaries are crossed and require urgent attention. Similarly, the United Nations Sustainable Development Goals (SDGs) might provide guidelines for the focus areas of climate robotics. Specifically, SDG 6 (Clean Water and Sanitation for All), SDG 13 (Climate Action), SDG 14 (Life below Water), and SDG 15 (Life on Land) are directly related to the scope of climate robotics.

Adaptation vs. Mitigation

Climate Adaptation projects are meant to help us adapt to the adverse impacts of the climate crisis. Mitigation projects seek to reduce the sources of greenhouse gases or enhance the sinks. This means that even while pursuing mitigation efforts, "we need to prepare for a warming world, which will have a

[67] Sutter, P. "We've Been "Close" to Achieving Fusion Power for 50 Years. When Will It Actually Happen?" *Space.com*, 14 Jan. 2024, www.space.com/when-will-we-achieve-fusion-power (Accessed January 20, 2024).
[68] Stockholm Resilience Centre. "Planetary Boundaries - Stockholm Resilience Centre." *Stockholmresilience.org*, 2023, www.stockholmresilience.org/research/planetary-boundaries.html (Accessed January 20, 2024).

host of known and unknown repercussions and in particular will acutely affect the most vulnerable populations of the world."[69] These two types of projects are necessarily symbiotic: "mitigate to make the adaptation process easier, while also adapting to give the mitigation process time to yield tangible results. We need both to optimize for the other."[70]

Most climate robotics use cases presented above fall into the mitigation category except three: coastal restoration, weather prediction and coral regeneration (which applications to both adaptation and mitigation). The other applications, wind energy generation, ocean data collection, seaweed sinking, cover crop seeding, solar panel cleaning, and waste management, fall largely within the mitigation category. However, this is a small sample of climate robotics solutions, which begs the question: Does this skewed pattern hold true with a much more extensive selection of solutions?

This is an important question and one that the Climate Robotics Network is actively researching. Why? "Currently, only 7% of global climate funding is being allocated to adaptation projects."[71] Moreover, the new 2024 report on Climate Adaptation by the Global Center on Adaptation found that the budget allocated to adaptation has recently decreased. [72] Meanwhile, we know that "material and sustainable outcomes from mitigation activities will require years, and in the interim period, countries need to invest heavily in adaptation. Climate Tech has an important role to play in filling the adaptation funding gap, yet there is little sector-wide consensus on what the adaptation solution set looks like. Fleshing out the scope of adaptation technologies and the specific barriers they face is a critical step in ensuring more equitable development of Climate Tech."[73]

The significant role of Venture Capitalists in this context must not be overlooked. One of the largest US VCs active in the climate and robotics space stated at a robotics investment conference in June 2024 that they focus exclusively on investing in startups building climate mitigation solutions because "there's still time." Other VCs argue that "climate adaptation won't happen without first undertaking Climate Automation," wherein robotics has an essential role to play.[74] Either way, it is essential to inform VCs that they harbor significant social responsibility when they decide to invest in climate robotics startups. The "micro-motives" of VCs chasing 10x returns in 5 years may lead to "macro-behaviors" that produce low-impact climate robotics solutions.

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69 *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).

70 Wyne, J. (2023) *Jamil Wyne on linkedin: Was great to speak with Michelle Ma from Bloomberg News About Climate Tech*. Available at: https://www.linkedin.com/posts/jamilwyne_was-great-to-speak-with-michelle-ma-from-activity-7130582694421241856-55uq (Accessed: 15 January 2024).

71 *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).

72 *ADD REFERENCE*

73 *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).

74 Kapoor, J. (2024) *Climate automation: Dirty jobs and a warming planet*, *LinkedIn*. Available at: https://www.linkedin.com/pulse/climate-automation-dirty-jobs-warming-planet-jay-kapoor-hdyle (Accessed: 15 January 2024).

Government funding and policies play an essential role in the research, development, and deployment efforts. Thanks to the public engagement to the climate issue, various funding programs are established in the intersection of climate and technology. These funding programs are especially increased in the last decade, providing resources for fundamental and convergent research, establishing and supporting for-profit companies, and forming community networks.[75] At the same time, climate action laws are getting passed on multiple fronts, often having positive consequences for the technology developers. For example, banning certain materials in product packaging has a potential to make it easier for robots to classify the items during waste sorting. In the same application domain, some new technologies, like watermarking the products, aims to directly help the robotic sorting system. We argue that technological opportunities should be a strong consideration in the discussion and adoption of new policies, while prioritizing the adaptation and mitigation efforts.

The Climate Robotics Network's Global Map of Climate Robotics enables us to determine whether robotics applications cut across both mitigation and adaptation/resilience-building efforts. The initial results show that 36% of climate robotics startups are classified as working on climate mitigation, 30% on adaptation, and 34% on both mitigation and adaptation.[76] As such, the distribution of applications appears to be more uniform, suggesting that robotics may offer a cross-cutting solution set for climate action.

In any event, the Network is partnering with key partners to encourage the global roboticist community to step up to the challenge of climate action. Inclusive adaptation coupled with mitigation is essential to enabling more climate-resilient communities.

Bits vs. Atoms

While some robotics technologies focus on data collection (i.e., bits), others focus on moving matter (atoms). In other words, some robotics solutions are exclusively used to collect data, while others predominantly move physical items. Naturally, some robotics technologies do both explicitly.

Robots have a distinct advantage when collecting data in remote or extreme environments.[77] "Scientific climate research relies on collecting extensive data over large areas of the globe and across long time scales. This can be facilitated by robotic sensors that rove autonomously across the atmosphere and oceans. Data collection can be greatly accelerated by swarms of robots that work in parallel to cover large areas."[78] In the above case, the only solutions that focus on data collection exclusively are the

[75] See for example: U.S. National Science Foundation, "Convergence Accelerator Portfolio", link: https://new.nsf.gov/funding/initiatives/convergence-accelerator/portfolio; U.S. National Science Foundation, "Dear Colleague Letter: Research Coordination Network for a University-Community Climate Action Network (RCN-UCCAN)", August 9, 2024, link: https://www.nsf.gov/pubs/2024/nsf24115/nsf24115.jsp?org=NSF (Accessed: 10 January 2025).
[76] These figures does not include the 70+ startups that still need to be classified and added to the Global Map.
[77] Sponsored Content. (2023) *How uncrewed vehicles are assisting in Combating climate change*, *The Robot Report*. Available at: https://www.therobotreport.com/how-uncrewed-vehicles-are-assisting-in-combating-climate-change (Accessed: 15 January 2024).
[78] RoboTech (2023) *How can we utilize robots in climate change?*, *Medium*. Available at: https://medium.com/illumination/how-can-we-utilize-robots-in-climate-change-915cb21b47d9 (Accessed: 15 January 2024).

autonomous surface water systems deployed by Open Ocean Robotics to collect high-quality ocean data. Neverthless, a good portion of academic research focuses on the methods of environmental monitoring, levereging recent advances on swarm robotics for coordinated data collection and AI techniques to guide the data collection process.

In contrast, the startup AMP Robotics focuses on both bits and atoms. It uses computer vision and AI to collect and analyze data. Why? To identify different types of waste and then manipulate its environment. Indeed, AMP Robotics uses this data coupled with robotic control and manipulation to physically move different types of garbage to sort this waste for recycling. To some extent, R2Home's robotic glider also focuses on both bits and atoms. The glider enables lower-cost and higher-frequency atmospheric data collection thanks to the system's ability to return (move) the weather sensors back to their launch sites, thus making them reusable.

The remaining examples focus predominantly on moving matter. Inverto moves mangrove seeds; KiteKraft moves wind turbines into the sky; QUT moves baby corals; Seaweed Generation seeks to move and sink seaweed; EarthSense moves cover crop seeds; and Soltrex moves dirt off solar panels. Naturally, each of these solutions still collects data in the process. Still, this data collection is not the primary climate-related task of these solutions in the specific contexts described above.

Disney's lovable little robot perfectly demonstrates the full value add of robotics for climate action.

It's important to emphasize that robotics technologies can both assess (collect and analyze data) and assist (change the environment). In this sense, "robotics is the only way to bring AI into the real world."[79] Indeed, robotics serves as the bridge between the physical world and the digital world in a way that AI

[79] Wälchli, E. (2023) *Enzo Wälchli on LinkedIn.* Available at: https://www.linkedin.com/posts/ewaelchli_ai-robotics-aiforgood-activity-7144367303512539136--WmC (Accessed: 15 January 2024).

alone cannot. Take Disney's lovable little robot, Wall-E, for example. Wall-E uses AI, computer vision, and data analysis to distinguish between different types of materials for waste management and recycling. But that's not all. The little robot physically manages that waste by compressing it and stocking it in its correct place for recycling.

In short, robots can also *act* on their environment, not just sense it. They can actually *do* something about the environment they're sensing; they can do something about the bad news. They can take action.

Climate is physical, and robots are physical. They can physically reshape problems into solutions, and do so at scale. And not just in the movies! Like Wall-E, AMP Robotics is an excellent example of climate action.

It's worth noting that all autonomous robotics solutions use AI. As such, using the term "AI-powered robotics" is somewhat redundant, much like saying "sun-powered solar panels." The reverse is not necessarily true. Indeed, many AI solutions do not include robotics. Yet we don't refer to AI *sans* robotics as "robotics-deficient AI." In any case, this does not make Climate AI solutions any less valuable than Climate Robotics solutions. It's important to understand that the two terms and solution sets are somewhat connected yet distinct.

Mobile vs. Fixed Robotics

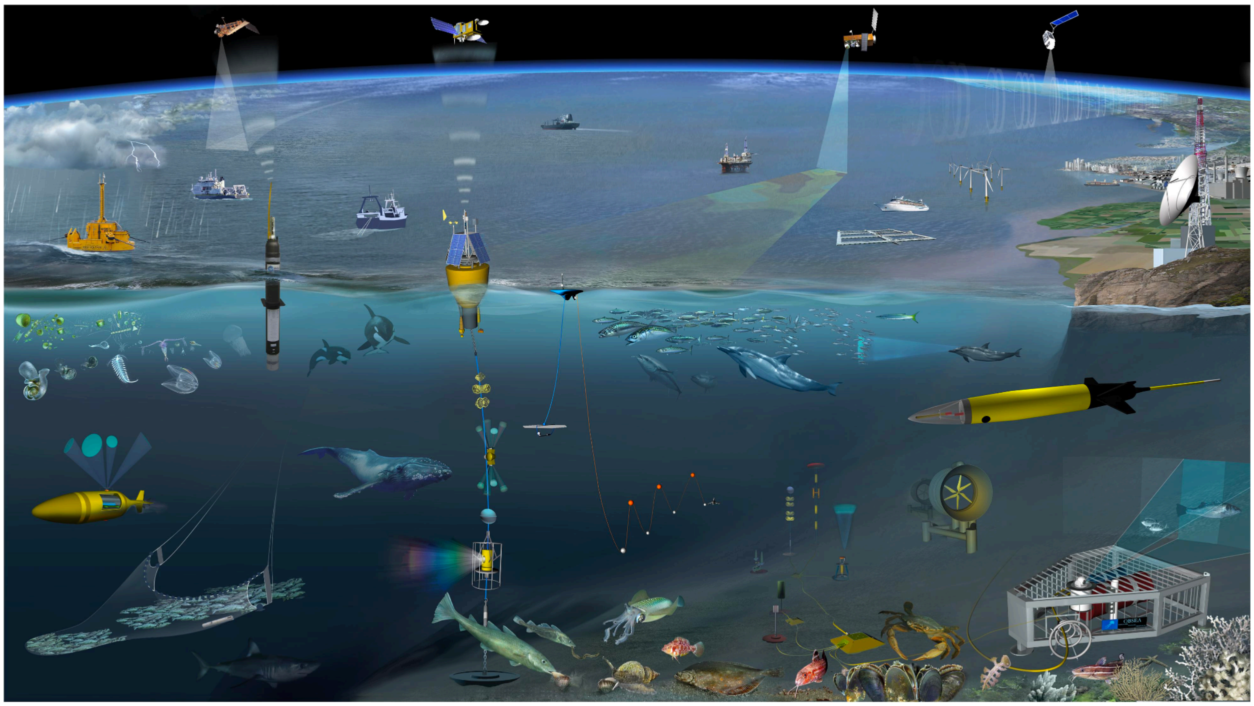
The use cases described in the previous section fall into the following categories of robotics: aerial, ocean, and ground robotics, as well as robotic arms. The first three in this list are often described as mobile robotics, a core field of robotics. These types of robotics solutions move across the spaces we humans occupy and go well beyond them, e.g., to the depths of the oceans and the heights of the stratosphere.

Aerial robots are often referred to as drones. Like other robots, drones come in various shapes and sizes, ranging from multi-rotor drones to fixed-wing drones and hybrid Vertical Takeoff and Landing (VTOL) drones that take off and land vertically like helicopters but transition to forward flight, like airplanes. Drones can use specialized sensors to monitor deforestation, wildlife populations, and air quality in real time. Aerial robotics can also transport and release cargo, such as seeds. As for climate disasters such as floods and hurricanes, drones can be used to locate survivors and map disaster damage.[80]

As for ocean robots, some are designed to float on the surface (sometimes called autonomous surface water vehicles), while others dive underwater (often called underwater robotics). Like their aerial counterparts, ocean robots can use a range of sensors for data collection and testing. They can "inspect and repair hydroelectric infrastructure, maximizing energy production from this renewable source" and

[80] See the online professional training on drones in humanitarian action created by lead author Patrick Meier: https://werobotics.teachable.com/p/aidrobotics

enable scientists to "explore ocean depths and study marine ecosystems more precisely."[81] They can also transport and release cargo such as seaweed. One challenge with underwater robots is that GPS and WiFi don't work underwater. That said, recent innovations in this space may overcome this challenge.[82]



A possible future of surface-water and underwater ocean robotics deployed to support climate action.

Ground robots are land-based systems that use wheels, tracks, or legs to move around. Not only can they collect a wide range of high-resolution data, but they can also collect cargo by picking fruits or collecting waste, for example. These robots can also transport said cargo. They have multiple applications in the climate context. Agriculture is a significant contributor to greenhouse gas emissions,[83] for example. Ground robotics can reshape this industry by promoting more sustainable practices and enhancing food security while minimizing their carbon footprint. "Through precision agriculture, robots can precisely apply fertilizers and pesticides, optimizing resource usage and reducing environmental impacts," for example.[84] Ground robots can also accelerate the construction of more sustainable buildings by reducing energy consumption and carbon emissions while improving passive thermal performance.

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[81] RoboTech (2023) *How can we utilize robots in climate change?*, *Medium*. Available at: https://medium.com/illumination/how-can-we-utilize-robots-in-climate-change-915cb21b47d9 (Accessed: 15 January 2024).
[82] Gent, Edd. "MIT Makes Low-Power Underwater Communication Practical - IEEE Spectrum." *Spectrum.ieee.org*, 15 Sept. 2023, spectrum.ieee.org/underwater-communication-low-power (Accessed: 20 Jan. 2024).

[83] Hannah Ritchie, Pablo Rosado and Max Roser (2024) - "Emissions by sector: where do greenhouse gases come from?" Published online at OurWorldInData.org. Available at: https://ourworldindata.org/emissions-by-sector (Accessed: 17 January 2024).
[84] RoboTech (2023) *How can we utilize robots in climate change?*, *Medium*. Available at: https://medium.com/illumination/how-can-we-utilize-robots-in-climate-change-915cb21b47d9 (Accessed: 15 January 2024).

Humanoid robots are “human-like” bipedal ground robots. While humanoids are attracting considerable attention and funding at the moment, there viability and value-add is hotly debated. Fact is, wheels are consistently more efficient than legs in most scenarios. Many unstructured environments are better suited to wheeled systems.[85] Some argue that wheeled robots can delivery 80% of the functionality of a humanoid robot at just 20% of the cost.[86] General-purpose robots do not need to take on a humanoid form to be effective. “AI-powered robots can be versatile and effective without adopting a humanoid form factor.”[87] In short, it remains to be seen where humanoids land in the coming years. What is clear, however, is that the billions of dollars pouring into humanoids will have positive spillover effects into other areas of robotics.

In contrast to the different types of robotics solutions described above, (industrial) robotic arms are generally dedicated to certain tasks at a fixed location. An example is AMP Robotics. The company’s arms move to sort and pick through trash. But they’re mounted to a fixed base, while the robotic arm contains multiple joints acting as axes that enable a degree of movement. Robotic arms can also be attached to mobile robots like aerial, ocean, and ground robots. In any event, robotic arms are another leading area of robotics.

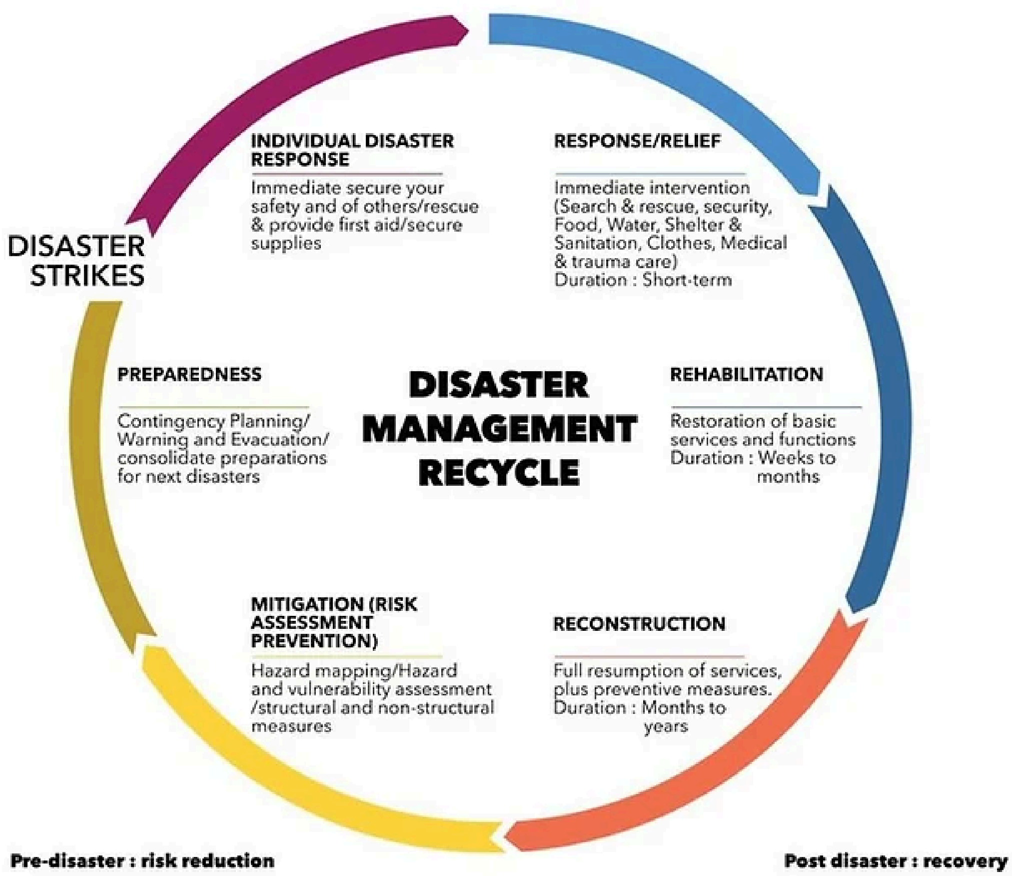
An important aspect of this discussion is the operation of robots in ***structured*** or ***unstructured*** environments. Conventional robotics technology is geared towards structured environments, where the conditions are (more or less) under control. For example, lighting conditions, the locations of objects in the scene, and obstacles around the robot can be controlled to a degree for industrial robotics tasks, whereas these parameters often vary drastically in mobile robotics applications. Most recent advances in robotics and AI are targetted towards making robots more robust and capable in unstructured settings.

What’s less clear are the kinds of robotics advances essential to expanding the value add of aerial, ocean, ground, and arm robotics for climate action. For example, might certain developments in bioinspired robotics or soft robotics help unlock new and more sustainable climate robotics solutions? Will micro- and nanorobotics also have a role to play in the future? If so, which kinds of breakthroughs are necessary? What critical research questions must roboticists prioritize to support climate action? And where do humanoid robots fit into Climate Tech?[88]

[85] Ziegler, L. https://www.linkedin.com/posts/zieglerr_to-humanoid-or-not-to-humanoid-that-is-the-activity-7282738199053918209-H69D (Accessed 10 January, 2025).
[86] Ziegler, L. https://www.linkedin.com/posts/zieglerr_to-humanoid-or-not-to-humanoid-that-is-the-activity-7282738199053918209-H69D (Accessed 10 January, 2025).
[87] Ziegler, L. https://www.linkedin.com/posts/zieglerr_to-humanoid-or-not-to-humanoid-that-is-the-activity-7282738199053918209-H69D (Accessed 10 January, 2025).
[88] Meier, Patrick (March 2023). “What is the Net Climate Impact of 1 Billion Humanoid Robots.” LinkedIn Article. Available at: https://www.linkedin.com/pulse/what-net-climate-impact-1-billion-humanoid-robots-patrick-meier-phd-atuhe

Sudden vs. Slow Onset

The climate crisis is a planetary-wide emergency. This emergency increases the frequency and magnitude of extreme weather events and climate-related disasters. A sudden-onset disaster is triggered by a hazardous event that emerges quickly or unexpectedly. These include floods, cyclones, landslides, and wildfires, for example. In contrast, a slow-onset disaster, such as drought, heatwaves, desertification, rising sea levels, and epidemic diseases, emerges gradually.



A conceptual framework for climate robotics ought to draw on the insights from disaster management.

The climate robotics solutions presented above are being deployed more in response to "slow burn" disasters like deforestation, biodiversity loss, pollution, warming oceans, and waste. We didn't include use cases focused on climate-related disasters because the field of "Humanitarian Robotics" is already well-established relative to Climate Robotics.[89] The deployment of civilian drones (aerial robotics) for

[89] Lead author Patrick Meier has extensive experience in developing and deploying Humanitarian Robotics, Humanitarian AI and Humanitarian Tech solutions in the context of humanitarian disasters including climate-related disasters. See WeRobotics.org and UAViators.org, for example. The following book documents Humanitarian AI & Robotics in action: Meier, P. (2015) *Digital Humanitarians: How Big Data is changing the face of humanitarian response*. Boca Raton: CRC Press.

disaster response is well documented and stretches back over a decade. "Mitigating climate disasters requires fast response in unpredictable and unstable environments. Robotic systems can assist in responding to the predicted increase in floods by rescuing victims and assisting with post-flood recovery. Similar roles for robots can apply to wildfires."[90]

Humanitarian and Climate Robotics will continue to converge due to the climate crisis. As such, both fields must talk to each other and join forces. As a first step, there may well be value in drawing on the disaster cycle framework to enable more precise discussion on climate robotics.[91] This framework defines several phases of the disaster cycle, including Response, Recovery, Prevention, and Preparedness. Adding these phases to the conceptual framework for climate robotics may be particularly insightful in the context of climate-induced disasters.

In any case, we need to learn from the Humanitarian Robotics community about how to respond to emergencies, only at a genuinely planetary scale, the likes of which we've only really seen with the COVID-19 response.[92]

Incremental vs. Transformative Progress

Robotics opens up numerous possibilities across various application domains, and climate robotics is no exception. Robots can contribute by replacing humans in processes, making task execution safer, more efficient, and economically viable. This represents an ***incremental*** contribution, as the robot enhances an existing process. Alternatively, robots can enable entirely new methods for achieving climate-related tasks. Such contributions are ***transformative***, as they accomplish goals that would be impossible without robotic technology. For instance, waste-sorting robots exemplify incremental progress, while underwater robots capable of taking measurements beyond human reach illustrate transformative advancements. While developing a system, systematically considering both solution spaces could help the innovation process.

Level of Autonomy

Robotic solutions can exhibit varying levels of autonomy. At one end of the spectrum, robots can be ***fully tele-operated*** through human inputs, often used for the safe remote execution of tasks. At the other end are ***fully autonomous*** robots that require no human input, ideally being robust to task variations and capable of recovering from failure modes. Full teleoperation demands constant attention and a high level of expertise from the human operator. Conversely, achieving full robot autonomy, especially in unstructured environments, poses significant challenges and requires long-term development efforts. Between these extremes, ***human-robot collaboration***

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[90] RoboTech (2023) *How can we utilize robots in climate change?*, *Medium*. Available at: https://medium.com/illumination/how-can-we-utilize-robots-in-climate-change-915cb21b47d9 (Accessed: 15 January 2024).
[91] *Phases of Disaster Recovery: Emergency response for the long term - world* (2013) *ReliefWeb*. Available at: https://reliefweb.int/report/world/phases-disaster-recovery-emergency-response-long-term (Accessed: 15 January 2024).
[92] This input was provided by Dr. Andrew Schroeder at Direct Relief.

schemes enable humans and robots to work together. Compared to fully tele-operated robots, well-designed collaborative schemes significantly reduce the cognitive and physical burden on the human operator. Additionally, part of the decision-making process can be handled by humans, reducing the risk of failure.

Challenges of Climate Robotics

The design, development, deployment, funding, and evaluation of climate robotics solutions face many challenges.[93] One reason the Climate Robotics Network was established is to tackle these many challenges collectively. This section highlights specific challenges around Top-Down Approaches, Techno-Centric Thinking, Lack of Evidence and Accountability, Lack of Research and Engagement, Financing and Affordability, Safety, Privacy and Governance, Simplicity, Maintenance and Repairability, Sustainability and Environmental Impact, and Regulations. We invite the broader community to propose possible solutions for these challenges. We propose our solutions where we can.

Top-Down Approaches

Foreign-led and top-down approaches tend to exclude local knowledge, expertise, agency, ownership, and leadership. This can and *does* have disastrous consequences, as exemplified by the painful history of failed top-down humanitarian and development projects over many decades.[94]

A simple analogy explains why foreign-led approaches have been known to cause harm: "If your life depends on your ship coming through rough weather, you would surely prefer a successful captain with long experience to, say, a brilliant physicist who had analyzed the natural law of sailing but who had never actually sailed a vessel."[95] To take this further, you would prefer a successful *local* captain with lived experience in the local waters you find yourself in, unlike a brilliant foreign captain who has never set sail in your parts. You would want a captain who knows all the local stories of wind patterns and undercurrents. This explains why captains of large freighters or cruise ships typically cede control of their vessels to local pilots, who bring the large ships into harbors and their docking areas.

"This sensible procedure, designed to avoid accidents, reflects the fact that navigation on the open sea (a more 'abstract' space) is the more general skill. While piloting a ship through traffic in a particular port is a highly contextual skill. We might call the art of piloting a 'local and situated knowledge.' What the pilot knows are local tides and currents along the coast and estuaries, the unique features of local wind and wave patterns, shifting sandbars, unmarked reefs, seasonal changes in microcurrents, local traffic conditions, the daily vagaries of wind patterns off headlands and along straits, how to pilot in these waters at night, not to mention how to bring many different ships safely to berth under variable

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[93] Guenat, S. *et al.* (2022) ***Meeting sustainable development goals via robotics and Autonomous Systems***, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).

[94] See the following case study authored by Patrick Meier, for example: *The dangers of foreign-led, top-down, techno-centric solutions*. *WeRobotics*. Available at: https://werobotics.org/blog/the-dangers-of-foreign-led-top-down-techno-centric-solutions (Accessed: 15 January 2024).

[95] Blog post authored by Patrick Meier: *Why the power of local matters and why international organizations.. WeRobotics*. Available at: https://werobotics.org/blog/why-the-power-of-local-matters-and-why-international-organizations-wont-unless (Accessed: 15 January 2024).

conditions. Such knowledge is particular, by definition; it can be acquired only by local practice and experience."[96]

The trouble with the Climate Tech space is that most "captains" (typically white, male, Western engineers) and their "ships" (foreign companies and startups) often ignore local knowledge and expertise.[97] They fall into the trap of "seductive reductivism" and focus on readily solvable problems.[98] Engineers are particularly prone to falling into such traps. As one Climate Tech founder lamented during a talk at Climatebase, "The Climate Tech space is still an industry of engineers. And that's a problem." The solution to seductive reductivism is quite simple if we can get our egos out of the way: listen to local experts; truly listen and value their expertise. "Local engagement is critical to ensuring climate inclusion in climate tech."[99]

A conceptual framework on climate robotics must take "localization" into account. While this term is more widely used (and debated) in the context of humanitarian action, it is no less essential to climate robotics. "In the humanitarian sector, localization means empowering local responders in affected countries to lead and deliver humanitarian aid. It aims to strengthen the capacity and resources of local organizations to respond to crises and promote long-term sustainability. This approach recognizes the importance of local knowledge and cultural understanding in providing effective and culturally appropriate aid. By empowering local actors, localization aims to improve the relevance, efficiency, and impact of humanitarian interventions."[100]

Localization means a genuine decentralization and shift in power. Localization prioritizes diversity, equity, inclusion, local expertise, leadership, and lived experience over technical solutions. This stands in contrast to foreign-led, top-down, and techno-centric approaches to humanitarian action, which are rarely sustainable. The same dangers of top-down approaches exist in researching, developing, and evaluating climate robotics solutions. Thankfully, some proven localization models exist to expand the space for locally-led action. One such model is the Inclusive Network Model, co-created by WeRobotics and Flying Labs. The model has been fully implemented in 40+ countries across Africa, Asia, Latin America, Central America, and the South Pacific.[101]

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96 Blog post authored by Patrick Meier: *Why the power of local matters and why international organizations.WeRobotics*. Available at: https://werobotics.org/blog/why-the-power-of-local-matters-and-why-international-organizations-wont-unless (Accessed: 15 January 2024).

97 This applies to equally research conducted on Climate Tech including this white paper on Climate Robotics. All co-authors of this report are male. This is an absolute failure on our part. While we invited 2 female colleagues to join as co-authors, and invited 3 female colleagues as well as 4 colleagues who identify as BIPOC to review this draft, the timing didn't work out for them to get involved. We pledge to redouble our efforts to create more inclusivity and diversity in the co-authoring and review of the final version of this report when it is published in May 2024.

98 Martin, C. (2019) *The reductive seduction of other people's problems*, *Medium*. Available at: https://brightthemag.com/the-reductive-seduction-of-other-people-s-problems-3c07b307732d (Accessed: 15 January 2024).

99 *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).

100 *European Civil Protection and Humanitarian Aid Operations*. Available at: https://civil-protection-humanitarian-aid.ec.europa.eu/what/humanitarian-aid/localisation_en (Accessed: 15 January 2024).

101 Disclaimer, the author is a co-founder of WeRobotics and former Executive Director. More on the model at: *Here's how we expanded locally-led action to shift the power (report)*. *WeRobotics*. Available at: https://blog.werobotics.org/2022/03/09/heres-how-we-expanded-locally-led-action-to-shift-the-power (Accessed: 15 January 2024).

Women from a school in Zanzibar, learning about the use of aerial robotics for coastal management.

In sum, when discussing climate robotics, we must ask: “Who?” Who gets to research, develop, and lead deployments of climate robotics solutions? Who benefits? Who gets to be an expert? Whose knowledge counts? Who makes the decisions? Who gets to make a career out of this new field?

Techno-Centric Thinking

In *Toward a Rational Society* (1970), the philosopher Jürgen Habermas describes “the colonization of the public sphere through the use of instrumental technical rationality. In this sphere, complex social problems are reduced to technical questions, effectively removing the plurality of contending perspectives.” This explains why today's social problems are often described in ways that make them appear as susceptible to technical solutions.[102]

[102] See blog post authored by Patrick Meier, *Technology for good is broken. Here's how we're trying to fix it. WeRobotics*. Available at: https://werobotics.org/blog/technology-for-good-is-broken-heres-how-were-trying-to-fix-it (Accessed: 15 January 2024).

“The significant risk, of course, is that a focus on the technological aspects of a problem can restrict our attention to merely those aspects. A computing lens can have the effect of masking and pulling political capital away from other and more insidious facets of a problem, as well as other (non-technical) means of addressing it.”[103] The problems we're facing are never just technical problems, which means that the solutions to these problems cannot be technical alone. Solutions must be social, inclusive, plural, and diverse.

Experts on the deployment of aerial robotics for positive social impact from the Flying Labs Network.

As such, when climate robotics solutions get deployed by technology startups and companies, the latter may have less experience in community engagement, multi-cultural communication, localization, and shifting the power, for example. This is especially true when climate tech solutions are designed and developed in one country/continent and deployed in another, where culture, language, customs, and ways of being may be entirely different.

A lack of awareness of such differences, coupled with a techno-centric mindset, has already caused harm and other types of unintended consequences in the field of Humanitarian Technology. The Climate Tech space must avoid repeating these mistakes. The Climate Robotics Network has deep experience and expertise in these areas, including intersectionality. The term was coined by American civil rights advocate and leading scholar of critical race theory, Kimberlé Williams Crenshaw.[104] It studies overlapping or intersecting social identities and related systems of oppression, domination, or discrimination. The network is readily available to guide startups, companies, and organizations to ensure the ethical, inclusive, and responsible deployment of climate robotics worldwide.

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[103] See blog post authored by Patrick Meier, *Technology for good is broken. Here's how we're trying to fix it. WeRobotics*. Available at: https://werobotics.org/blog/technology-for-good-is-broken-heres-how-were-trying-to-fix-it (Accessed: 15 January 2024).
[104] Taylor, Bridie (2019) *Intersectionality 101: What is it and why is it important? Women Worldwide*. Available at https://www.womankind.org.uk/intersectionality-101-what-is-it-and-why-is-it-important (Accessed: 4 January 2024).

In short, a techno-centric approach to deploying climate robotics solutions will fail and, at best, be unsustainable. At worst, it will cause actual harm. Given how heavily this White Paper leans on technical solutions to make the case around robotics, we're particularly mindful of this point. We recognize that tech solutions run the risk of “a form of technological determinism,” thus “missing the need for broader reforms, including over who owns and controls tech itself.”[105]

Lack of Evidence and Accountability

The evidence base for the value-added contribution of robotics to climate action is particularly thin since the solutions and applications are relatively new. As a result, the knowledge base is equally thin and fractured across hundreds of startups, companies, and research labs. No open repositories document best practices, successes, failures, or lessons learned—both in terms of the technology and deployment methods, not to mention business models. There are few publicly available independent evaluations of climate robotics in action and few shared spaces—such as conferences and workshops—for open and cross-disciplinary discussions dedicated to knowledge sharing and building the evidence base of climate robotics.

This vacuum enables hype to flourish. It also leads to failed investments, squandered funding, and unintended or unexpected consequences. For example, we don’t yet fully know the environmental impact of deploying ocean robotics at scale in the context of seaweed sinking. Some marine scientists have expressed grave concern that doing so could reduce oxygen levels in parts of the ocean, which could have disastrous effects on marine life.

Humanitarian UAV Code of Conduct

We must tackle this vacuum head-on to ensure the climate robotics space can have a responsible and meaningful impact. In addition to documenting and growing the evidence base, best practices, and failures, we also need to hold ourselves accountable as a community. Indeed, it remains to be seen how

[105] Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).

climate robotics will be regulated and who might own the resulting data.[106] This is why the Climate Robotics Network is developing a Code of Conduct for Climate Robotics. The Humanitarian UAV (Drone) Code of Conduct may be an ideal starting point.[107]

Lack of Research and Engagement

There needs to be more research on where robotics can have the most impact in the climate space. Likewise, few efforts seek to identify what advances in robotics are necessary for robotics to offer novel solutions or radically improve existing climate solutions. Given this general lack of awareness and understanding around necessary and urgent applications, there's a shortage of roboticists tackling the climate crisis.[108] It's also clear that roboticists need to rethink their role in the climate crisis.[109] The lack of robust research also runs the risk of VCs and donors funding robotics solutions that are low-priority in relation to climate priorities.

Financing and Affordability

A growing number of founders and investors argue that hardware is the missing piece to solving the climate tech puzzle.[110] "While software companies have traditionally been the focus of venture investment in the tech sector, it's time for us to emphasize a different approach. Hardware companies, or those that design and manufacture physical products, have the potential to make even greater strides in the fight against climate change." One VC argues that "While software can leverage data analytics to forecast and identify energy and carbon emission reduction opportunities, it's hardware that translates these insights into action. For instance, implementing hardware controls within building systems empowers owners and operators to enhance equipment efficiency, leading to decreased energy and water usage."

Financing for startups is increasingly challenging, however, especially for startups focusing on hardware where they face more daunting CapEx and OpEx challenges. Hardware development presents a range of challenges that are less pronounced in software development. "Hardware is hard," as the saying goes. While some argue that these difficulties are exaggerated, there's a difference between developing a simple piece of mechanical hardware and developing hardware solutions that enable the safe and mobile operation of autonomous robotics, especially in the "wild."

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106 Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).

107 See the Humanitarian UAV Code of Conduct at https://uavcode.org, for example. Disclaimer: the lead author spearheaded the development of these principles.

108 Chen, S. (2023) *How roboticists can tackle climate change*, *IEEE Spectrum*. Available at: https://spectrum.ieee.org/robotics-climate-change (Accessed: 15 January 2024).

109 Vial, J. (2023) *Roboticists need rethink on Climate Change Role*, *Business News*. Available at: https://www.businessnews.com.au/article/Roboticists-need-rethink-on-climate-change-role (Accessed: 15 January 2024).

110 https://www.fastcompany.com/90989514/why-hardware-is-the-missing-piece-to-solving-the-climate-tech-puzzle

One of the leading VCs for early-stage robotics startups argues that "robotics is a unique investment class," which needs its own framework and metrics.[111] Robotics Invest 2024, an invite-only meeting of VCs and startups, served as a call to action to VCs: co-create the investment mechanics for this unique class. Founders of robotics startups are more likely to trust and build higher-quality partnerships with investors who understand why robotics presents a different investment class.

Some VCs are encouraging climate robotics startups to bring down their OpEx by making their robots more general while keeping the same bill of materials.[112] The CEO of one successful climate robotics startup advocates for building robotics solutions that can scale climate technologies across the life cycle of said technologies. For example, if a robot is designed to help install solar panels, that robot same should also be able to remove said panels for recycling purposes. Others advocate for solutions that generate "greater productivity and efficiency" because these "solve for climate."[113] All emphasize the importance of being obsessed with their clients' problems to unlock stellar unit economics.

The CEO of another successful climate robotics startup likes to ask: "Does your climate robotics startup pass the Mr. Burns test? She emphasizes the importance of building a product that Mr. Burns (the greedy capitalist from the animated series The Simpsons) would buy not because it scales climate action but because it's the best, cheapest, and most convenient. That's the key to climate impact at scale. In contrast, some CEOs who have exited from previous startups are now building climate robotics are steering clear for VCs and focusing on bootstrapping, grant funding, paid demos and/or creating an early pipeline of paid clients before building their full robotics stack.

The finance gap for climate tech is estimated to be around $2 trillion dollars.[114] Aside from a few exceptions in the Venture Capital (VC) space, there needs to be significantly more funding available for early-stage startups in the robotics space. Indeed, "35% of the emissions reductions needed by 2050 will come from technologies not yet at commercial scale."[115]

Moreover, while talent is evenly distributed, opportunity certainly isn't. Entrepreneurs in the Majority World (the so-called Global South) have nowhere close to equal access to financing opportunities. Meanwhile, VCs that do fund climate tech startups often lack experience or expertise outside the Global North. This is equally true of the startups they invest in, which often leads to top-down approaches and techno-centric thinking when these startups deploy their technologies in the Majority World.

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[111] https://www.linkedin.com/pulse/how-build-invest-robotics-startups-patrick-meier-phd-a3n0e

[112] https://www.linkedin.com/posts/meierpatrick_climatetech-activity-7206616676761485312-VLfy

[113] https://www.linkedin.com/posts/meierpatrick_climatetech-activity-7206616676761485312-VLfy

[114] Herweijer, D. and Barry O'Byrne. "Why Climate Tech Desperately Needs More Financial Backing." *World Economic Forum*, 12 Jan. 2024, www.weforum.org/agenda/2024/01/why-climate-tech-desperately-needs-more-financial-backing (Accessed 21 Jan. 2024).

[115] Herweijer, D. and Barry O'Byrne. "Why Climate Tech Desperately Needs More Financial Backing." *World Economic Forum*, 12 Jan. 2024, www.weforum.org/agenda/2024/01/why-climate-tech-desperately-needs-more-financial-backing (Accessed 21 Jan. 2024).

This runs the risk of further amplifying inequalities and power asymmetries between those building and deploying robotics solutions and marginalized communities at the front lines of the climate crisis. There is already a “broad consensus that climate tech is neglecting vulnerable communities.”[116] Many experts already warn that climate tech solutions are not reaching communities that need them the most.[117]

Others point out that the deployment of robotics systems will “reinforce existing inequalities because ‘through the course of history […] automation has always had a tendency to ease the accumulation of wealth, typically benefiting those who are already wealthy.’”[118] These inequalities could also be “intensified by a transformed job market, as the need for low-skilled workers would decrease as ‘low skilled, mundane and routine tasks can be automated.’”[119]

The cost of robotics solutions has plummeted in recent years, but cost is always relative. What is considered affordable in the so-called “Global North” may not be in the informal settlement of Mathare outside Nairobi. As noted during the panel on “Climate Robotics in the Majority World” held at the 2024 Climate Robotics Summit, just obtaining a Raspberry Pi in Nigeria takes many months and costs far more than buying a Raspberry Pi in England, for example.

From the different types of robotics categories described above, aerial robotics (or drones) are still the most accessible climate robotics technologies, partly because the drone industry has responded to massive consumer demand for accessible drone technology. In contrast, demand for ocean and ground robotics, like robotic arms, is still industry-driven.

It remains to be seen how much demand exists for more affordable climate robotics solutions and whether the startups behind these solutions can develop viable business models and secure the funding they need to deliver their products. That said, we shouldn’t discount the “DIY robotics” space, particularly outside the Global North. This approach prioritizes affordability as a critical design priority.

Take a Tesla vehicle, for example, which costs upwards of USD 40,000, not to mention the USD 2,400 annual subscription for the autonomous, self-driving feature. Meanwhile, an engineer in India has reportedly turned his USD 5,000 car into an autonomous vehicle using a simple USD 150 smartphone.[120] This DIY approach may scale Climate Robotics more quickly than an industry-led approach alone. Open-source solutions are equally vital in scaling Climate Robotics, not least as robotics become increasingly integrated into digital public infrastructure.

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[116] *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).
[117] *The Climate Tech Opportunity* (2023). *Oxford Climate Tech Initiative*. Available at: https://www.oxclimate.tech/the-climate-tech-opportunity (Accessed: 15 January 2024).
[118] Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).
[119] Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).
[120] Mayank, M. (2023) *Mohit Mayank on LinkedIn.* Available at: https://www.linkedin.com/posts/imohitmayank_opensource-ai-ml-activity-7146369149114519552-zi0i (Accessed: 15 January 2024).

A local engineer takes a more frugal approach to developing an autonomous self-driving vehicle in India.

Using robotics in climate action clearly faces several challenges including affordability, usability, and sustainability. This is why we're calling for a minimalist movement in climate robotics.[121] Minimalism is more than an esthetic, it's a design lens for sustainability. A minimalist approach to robot design has grown from a research topic in computer science theory to a matter of practical concern. Minimalist robot design emphasizes simplicity, efficiency, and adaptability within the scope of a specific task. For example, think of the commercial success of vacuuming, mowing, and cleaning robots, which all share similarly simple designs and algorithmic approaches (especially compared to, say, designing a humanoid robot for these tasks).

Many climate robotics startups in the Global Map of Climate Robotics don't appear to be minimalist when designing their solutions. This is often because commercially available platforms and components are designed with different objectives, such as maximizing speed or sensor resolution. This may become an issue for these startups as they scale: the kind of climate tech we need must be widely available *and* climate-friendly.

We believe minimalist climate robotics presents a promising approach to tackle the climate crisis for the following reasons:

1. **Lower Energy Consumption:** Minimalist robotics focuses on reducing the complexity of robotic systems, leading to lower energy consumption. These robots can maximize battery lifetimes and perform tasks with a smaller environmental footprint by minimizing the number of components and optimizing energy usage.

[121] Meier, Patick and Alexandra Niles (April 2024). "Embracing Minimalist Robotics to Tackle the Climate Crisis." LinkedIn Article. Available at: https://www.linkedin.com/pulse/embracing-minimalist-robotics-tackle-climate-crisis-meier-phd-cjwue

2. **Reduced Material Use:** Minimalist robotics promotes using fewer materials, leading to decreased resource consumption. This approach reduces the environmental impact of manufacturing and makes robots more cost-effective and accessible.
3. **Adaptability and Versatility:** Minimalist mobile robots can still be adaptable and versatile by leveraging embodied and collective intelligence. This flexibility allows them to be deployed in various sectors, from renewable energy infrastructure maintenance to environmental monitoring and conservation, making them valuable tools to support climate action.
4. **Ease of Maintenance and Repair:** Minimalist robots are easier to maintain and repair with fewer components and a simplified design. This extends their lifespan and reduces waste and the need for replacement parts, further contributing to sustainability.
5. **Scalability:** Depending on the task, minimalist robots can be scaled up or down more easily. This scalability makes them suitable for small-scale and large-scale applications, allowing for a more efficient response to the climate crisis. As the Internet of Things moves toward battery-less technologies, how can roboticists similarly minimize the impacts of large-scale technologies?

The concept of sufficiency is closely related to minimalism.[122] Sufficiency is a set of policy measures in daily practices that avoids the demand for energy, water, land, materials, and other natural resources while delivering well-being for all within the planetary boundaries. "Without sufficiency, we cannot innovate within the planetary boundaries." We must reframe Climate Tech to integrate the concepts of minimalism and sufficiency,[123] which combine ecological economics, biology, chemistry, energy, physics, political science, sociology, political philosophy, and justice theory. In sum, we can develop innovative, sustainable, and cost-effective solutions to tackle the climate crisis by embracing sufficiency and minimalist robotics.[124]

Lastly, some experts are concerned that investments in climate robotics might "divert resources away from more straightforward, less technologically driven approaches."[125] Project Drawdown has also argued that a highly disproportionate amount of funding goes to emerging technology solutions instead of existing solutions already proven to work. A panelist at the 2024 Climate Robotics Summit also stated that we need to intervene *less*, not more. "We need less AI, and more EI, Ecological Intelligence." The speaker emphasized that nature knows how to bounce back, which they're a proponent of nature-based solutions.

Sustainability and Environmental Impact

Just because robotics solutions don't directly make use fossil fuels doesn't mean they qualify as environmentally friendly or sustainable. Like any technology, the manufacturing and assembly process of

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122 See https://www.thesufficiencylab.org (Accessed 10 January 2025)

123 Meier, P. https://www.linkedin.com/posts/meierpatrick_can-we-adopt-sufficiency-as-a-design-lens-activity-7257405936992972801-hRla (Accessed 10 January 2025).

124 See also the concept of "lazy robotics" as described by Subramanian, S. and Wright, E. "Why the World Needs Lazier Robots." Washington Post, https://www.washingtonpost.com/climate-solutions/interactive/2024/ai-energy-consumption-robots (Accessed 10 January 2025).

125 Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).

robotics solutions has an associated carbon footprint.[126] Moreover, robotics solutions use rare earth minerals and draw on global supply chains. Documenting and understanding the life cycles of individual climate robotics solutions is thus imperative.[127] To be sure, "Moving towards sustainable robotics requires a rigorous multidisciplinary approach to understand how sustainability, technology, and societal challenges are intertwined."[128]

One principle that climate robotics startups ought to be mindful of, for example, is the concept of separability in recycling. For recycling to be effective, the materials that constitute a given product need to be separable. Seperability needs to be optimized during the design and prototyping phase to ensure that climate robotics solutions can be easily disassembled into separate pieces for recycling and thus to contribugte to the circular economy. "In fact, 80% of a product's environmental impact is influenced by decisions made at the design stage."[129] While robotic arms can be used to disassemble and separate some component parts, there's significant room for improvement, which can be achieved through deliberate and forward thinking design.

Robotics clearly have a role to play across the circular economy and life cycles of products and technologies. Take solar panels, for example. Robotics can be used to automate (and thus render more efficient) the manufacturing of panels, the physical deployment and installation of these panels, the maintenance of the panels and the subsequent disassembly, recycling and reuse of the paanels.

Roboticists also need to take more advantage of developments in bio-sourcing, alternative plastics and material sciences to reduce the environmental impact of their technologies at all phases of their technologies' life cycle. The new and important field of "sustainable robotics" is driving the integration of biodegradable materials into robotics hardware, which essential to minimize the carbon impact of climate robotics solutions in the coming years.[130]

Safety, Privacy, and Governance

Emerging technologies have always created or amplified safety and privacy issues. In many ways, robotics is no different. That being said, AI alone doesn't physically move around us like a mobile robot does. Robots also engage with us physically in a way that AI does not (hence the field of human-robot

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[126] Haidegger, T., et al. "Robotics: Enabler and Inhibitor of the Sustainable Development Goals." *Sustainable Production and Consumption*, vol. 43, 1 Dec. 2023, pp. 422–434, www.sciencedirect.com/science/article/pii/S2352550923002634 (Accessed 20 January 2024).

[127] Guenat, S. *et al.* (2022) *Meeting sustainable development goals via robotics and Autonomous Systems*, *Nature News*. Available at: https://www.nature.com/articles/s41467-022-31150-5 (Accessed: 15 January 2024).

[128] Haidegger, T., et al. "Robotics: Enabler and Inhibitor of the Sustainable Development Goals." *Sustainable Production and Consumption*, vol. 43, 1 Dec. 2023, pp. 422–434, www.sciencedirect.com/science/article/pii/S2352550923002634 (Accessed 20 January 2024).

[129] Mohr, S. et al. "Product Sustainability: Back to the Drawing Board," https://www.mckinsey.com/capabilities/operations/our-insights/product-sustainability-back-to-the-drawing-board (Accessed 10 January 2025).

[130] See for example Professor Mirko Kovac's work on sustainable robotics, https://www.empa.ch/web/s799 (Accessed 10 January 2025).

interaction). As such, robotics solutions face serious safety issues while facing many (if not all) of the same challenges confronting the AI and generative AI space, including governance, safety and privacy.[131] This includes data protection, biased training data, unlawful uses of personal identifying information, and hacking AI systems, which can and has led to genuine harm, for example.

Just like AI, we must also develop governance frameworks for Climate Robotics. "Governance must be understood as more than compliance to rules: the legislation is often lagging, and the rules and ethical standards are different across organizations and worldwide. It requires building a strong culture around sustainability and ethics."[132] Governance was a significant motivating factor for the launch of the Climate Robotics Network and the network's initiative to develop a dedicated Code of Conduct.[133]

Simplicity, Maintenance, and Repairability

Climate robotics solutions don't need to look like they just came out of a *Star Trek* future; they simply need to work. Over-engineered robotics solutions are likely to be more challenging to operate and maintain. They're also more likely to break than more straightforward solutions with fewer bells and whistles. While Silicon Valley continues to design *Star Trek*-like solutions for itself, the real world does not live in a *Star Trek* universe. This explains why the early-stage robotics startup Gather is explicitly focused on developing very simple farm robotics solutions, for example.

Too many startups and companies in the robotics space fail to understand just how vital simplicity is for technology adoption. They should take note of the many failed Humanitarian Tech solutions and companies that overlooked this fact over the past 10+ years. Creating simple robotics solutions requires *inclusive* innovation, which is more challenging than top-down, techno-centric approaches.[134]

To further extend the science fiction analogy, much of the world is better described as living in a *Star Wars* universe, where technology does break, often and in remote locations. Think R2D2, C3PO, and even the Millennium Falcon. But each of these advanced technologies is locally repairable by the end-users themselves.[135]

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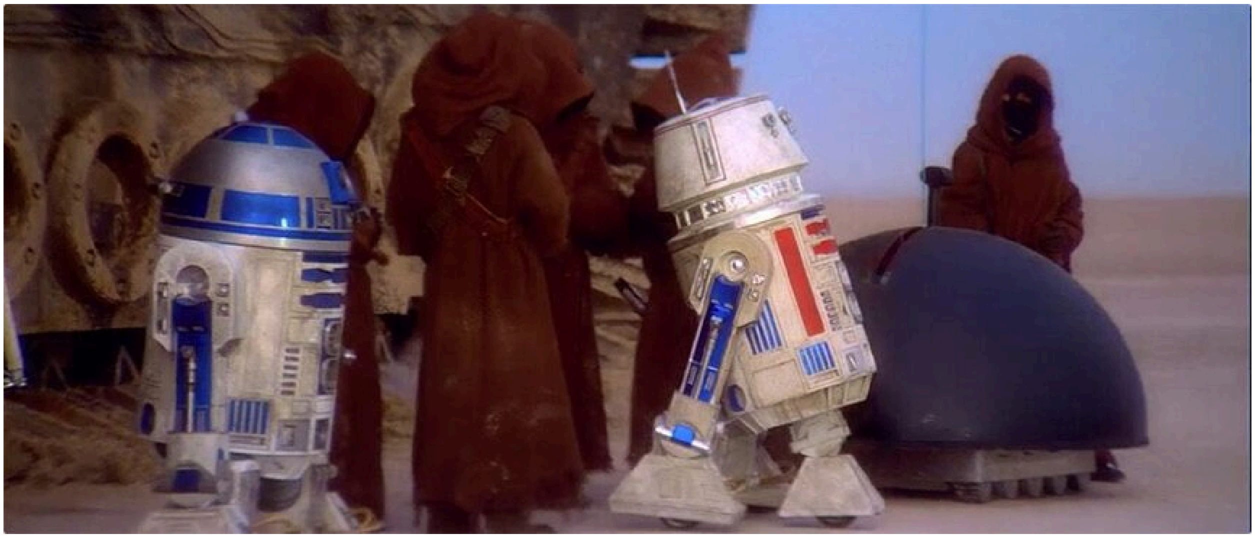
131 Mai, Vincent, et al. "The Role of Robotics in Achieving the United Nations Sustainable Development Goals—the Experts' Meeting at the 2021 IEEE/RSJ IROS Workshop [Industry Activities]." *IEEE Robotics & Automation Magazine*, vol. 29, no. 1, Mar. 2022, pp. 92–107, https://doi.org/10.1109/mra.2022.3143409 (Accessed: 20 January 2024).

132 Mai, Vincent, et al. "The Role of Robotics in Achieving the United Nations Sustainable Development Goals—the Experts' Meeting at the 2021 IEEE/RSJ IROS Workshop [Industry Activities]." *IEEE Robotics & Automation Magazine*, vol. 29, no. 1, Mar. 2022, pp. 92–107, https://doi.org/10.1109/mra.2022.3143409. (Accessed: 20 January 2024).

133 To learn more, please see: https://climaterobotics.network/resources.

134 See https://www.elrha.org/funding-opportunity/journey-to-scale; https://ssir.org/articles/entry/humanitarian_innovation_and_experimentation; https://www.thoughtworks.com/content/dam/thoughtworks/documents/blog/digital-innovation/blg_topic_scaling_innovations_missing_middle_03.pdf; https://www.icrc.org/en/document/evaluation-innovation-icrc-2018-2023; https://www.humanitech.org.au/humanity-first; and https://preparecenter.org/activity/ethics-in-technology.

135 See https://www.ewb.ca/wp-content/uploads/2018/08/EWB_FAILURE-REPORT_EN_03-08-2018-pages.pdf



What would happen to the Star Wars universe if end users weren't allowed or able to repair any droids?

In short, climate robotics technologies are not immune to Murphy's Law. Maintenance is thus essential to guarantee business continuity. Transferring climate robotics solutions that can't be maintained locally is a recipe for disaster. This creates external dependencies that are simply unsustainable. The "Right to Repair" movement must thus be extended to include robotics solutions.[136]

At the same time, because many climate robotics solutions are relatively new, the startups behind them may not yet have enough data to fully understand their tech's failure rates and main failure points, which can hamper preventive maintenance strategies. What's more, all kinds of issues around warranty and liability crop up when companies explore options around self-repair by end-users. It's one thing to solve this for mobile phones, but perhaps quite another for intelligent and autonomous robotics systems that move around urban areas.

Regulations

Regulations often lag behind innovation. In some cases, they eventually catch up and, at times, arguably overcompensate, which hinders further innovation. Finding the right balance between innovation and regulations is an ongoing challenge. Long permitting processes will necessarily deter innovation by creating barriers to entry. While substantial progress has been made in drone regulations (aerial robotics), it remains to be seen how other types of robotics solutions fare as they become more mobile and readily accessible.

The above analysis of problems is not necessarily exhaustive. Robotics solutions present several additional challenges.[137] At the same time, it's worth noting that many of these challenges are hardly

[136] *Right to repair* (2023) *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Right_to_repair (Accessed: 15 January 2024).
[137] Kobie, N. (2023) *Why cutting-edge innovation is killing the planet*, *ITPro*. Available at: https://www.itpro.com/technology/why-cutting-edge-innovation-is-killing-the-planet (Accessed: 15 January 2024).

unique to robotics. All the challenges described above were also true of the Humanitarian Tech and Humanitarian Robotics space during the early days (some still are).[138] We have a distinct advantage over these past efforts. Namely, we can learn from their mistakes and draw on their best practices and codes of conduct. As such, the Climate Tech community can benefit from these past learnings and insights to manage the challenges around applying emerging technologies for climate action.

[138] See WeRobotics.org and UAViators.org, for example. The following book documents Humanitarian AI & Robotics in action: Meier, P. (2015) *Digital Humanitarians: How Big Data is changing the face of humanitarian response*. Boca Raton: CRC Press.

The Climate Robotics Network

The Climate Robotics Network was founded to understand better how robotics solutions can support climate action in meaningful and inclusive ways. As such, the network has embarked on several projects spanning research, policy development, community building, and communications. This section provides an update on some of the network's key activities. These include Consulting Services, Summit on Climate Robotics, Global Mapping, White Paper Series, Deployment Code of Conduct, Communications, Engagement and Co-Creation.

Consulting Services

The Network already provides consulting services to several climate robotics startups. This consulting includes strategy, deal sourcing, applied research marketing and communications, deployment logistics, business development, partnerships, and more. The Network will also look to advise international organizations, donors, and VCs where and when appropriate. One of the network's distinct advantages is that it remains objective and independent.

Climate Robotics Summit

The purpose of the Summit is to connect the Climate Robotics Community and collectively build the evidence base for the added value of robotics in climate action. The Summit explored what is already happening in the climate robotics space along with the opportunities that climate robotics offers while tackling the many challenges identified in this White Paper. More information on the Summit agenda and speakers is available on the Network's website.[139] The knowledge and insights gained during the event have informed updates to the Global Map and this White Paper.

Global Map

The Climate Robotics Network's 'Global Map' provides a comprehensive overview of the climate robotics field. This resource includes well over 250 entries, encompassing a wide range of organizations, from startups to established companies and university programs. The map is a vital reference point for understanding the various initiatives and developments within the global climate robotics sector.

The map showcases a variety of applications of robotics in tackling climate-related challenges. Some examples include innovative approaches in agriculture that aim to increase efficiency and reduce environmental impact, initiatives in environmental monitoring that enhance climate adaptation strategies, and advancements in precision farming that promote sustainable agricultural practices. These examples represent the broader activities and contributions cataloged on the map, providing insights into specific advancements and efforts within these areas.

[139] Climate Robotics Summit: https://climaterobotics.network/summit

At its core, the Global Map is an effort to catalog key actors, their geographies, and respective projects in the climate robotics space. This makes it an invaluable tool for stakeholders, offering a clear picture of trends, potential areas for collaboration, and the geographic distribution of efforts in this dynamically evolving sector.

White Papers and Other Publications

The White Paper Series aims to build the knowledge base of the Climate Robotics space and inform the sustainable, responsible, and ethical deployment of robotics solutions to support Climate Action. The White Papers will develop the language and conceptual frameworks to enable more informed and rigorous discussions on climate robotics. They will help make sense of the risks, gaps, overlaps, priorities, and opportunities. The Series will also evaluate use cases and technologies to identify the most promising efforts in climate robotics. We also expect the network the foster transdisciplinary collaborations between experts in various fields and facilitate the publications of high impact venues. When possible, prioritizing open-access journals would boost the impact of such publications.

Code of Conduct

The Deployment Code of Conduct (CoC) aims to hold ourselves accountable by identifying the most important do's and don'ts in the field-testing and deploying Climate Robotics solutions.[140] The CoC will draw on existing codes of conduct and relevant principles to inform the do's and don'ts for those in the Climate Robotics space. The CoC will be an open and public living document. It will be updated at least once a year based on the input and feedback from the community.

Strategic Communications

The Network's communications aim to openly share knowledge of the climate robotics space while growing and engaging the community. This will be done through regular blog posts, LinkedIn posts, and short videos. The engagement from the community will serve to identify key areas of interest to said community, potential speakers and panelists for future events, and new deployments and research areas, along with new partnership opportunities.

In addition to the above activities, the Climate Robotics Network plans to launch a "Women in Robotics" channel and one on "Climate Robotics in the Majority World." The Network is also looking to create a "Job Board" channel and develop a STEM strategy to engage youth in the climate robotics space.

[140] See https://climaterobotics.network/projects (Accessed 10 January 2025).

Furthermore, the Climate Robotics Network plans to create a Knowledge Base of Best Practices and a Monitoring and Evaluation Framework. As part of this, there are plans to develop a "WALL-E Fail" initiative to create a safe and open space for sharing critical failures in the design and deployment of climate robotics solutions. This project aims to ensure lessons are learned and shared far and wide. In time, the Network will also create an Online Learning Academy to provide students, engineers, climate scientists, and entrepreneurs with an online virtual learning environment where they can expand their knowledge of Climate Robotics and receive a certificate of completion.

While networks are essential to Climate Action, we need *diverse* networks, including networks that expand the space for locally-led action, which is sorely lacking in Climate Tech. This poses several risks. If Climate Tech becomes synonymous with Big Tech and (Western) Global Institutions with their extensive networks of corporate clients, we'll exacerbate power asymmetries and inequality, which already hamper sustainable, inclusive, and equitable Climate Action. To be sure, "inequality remains one of the biggest barriers to the net zero transition."[141]

What is the Power Footprint of your organization and the biggest players in the Climate Tech space?

Western institutions, donors, and international organizations most often have a disproportionate amount of power relative to local and national organizations. This explains why the push for Diversity, Equity and Inclusion, Localization, and Shift-the-Power is essential. For these crucial efforts to be fully effective, however, they must also take our "Power Footprints" into account.[142] The Power Footprint of

[141] Garnett, Emma, et al. "Six Ways Inequality Holds Back Climate Action." *Phys.org*, 20 Jan. 2024, phys.org/news/2024-01-ways-inequality-climate-action.html (Accessed 21 Jan. 2024).
[142] The concept of the "Power Footprint" was developed and championed by lead author Patrick Meier when he served as Executive Director of WeRobotics.

an organization reflects the amount of authority, control, and influence that an organization exerts within a system.[143] Just like our Carbon Footprints, global institutions, international organizations, and prominent corporate players must pledge to take their own power footprints into consideration if they want to have a sustainable, inclusive and equitable impact in the Climate Tech space. The Climate Robotics Networks stands ready to assist in this journey.

The Climate Robotics Network is open; all are invited to join. Please do contact us to get involved: ClimateRobotics.Network.

[143] Meier, Patrick. "What Is the Power Footprint of International Organizations?" *WeRobotics*, 21 Oct. 2021, werobotics.org/blog/power-footprint-ingos (Accessed 21 Jan. 2024).

Instead of a Conclusion: Open Questions and Next Steps

"Addressing the interconnected challenges of sustainability, climate change, and biodiversity decline requires solutions to measure our planet and generate the knowledge needed to protect, manage, and restore its resources. Robots make these solutions more efficient, scalable, and cost-effective."[144] In short, robotics can serve as a force multiplier for Climate Action by enabling rapid deployments at scale.

Real-world use cases for climate robotics include scaling the deployment of existing climate solutions.

While "Robotics is not a de facto solution to complex global problems, such as systemic economic crises, climate change or the transformation of work, yet it offers a partial remedy."[145] Climate Robotics represents a convergence of technological innovation and environmental commitment. This convergence is significant because it enables rapid scaling of solutions, precise execution of complex tasks, and innovative approaches to longstanding environmental challenges. Faced with the defining issue of our time, the climate crisis requires a multifaceted response, one where every available technology, including robotics, is appropriately leveraged to mitigate its effects and foster responsible adaptation. This white paper aimed to explore the potential of robotics, demonstrating how they can enhance existing solutions and pioneer novel ones in our urgent battle against climate change.

[144] Mintchev, S. (2023) *Stefano Mintchev on LinkedIn: A great and very timely initiative led by Patrick Meier, PhD.* Available at: https://www.linkedin.com/posts/stefanomintchev_climate-robotics-climaterobotics-activity-7138424948255035392-z1Uz (Accessed: 15 January 2024).

[145] Haidegger, T., et al. "Robotics: Enabler and Inhibitor of the Sustainable Development Goals." *Sustainable Production and Consumption*, vol. 43, 1 Dec. 2023, pp. 422–434, www.sciencedirect.com/science/article/pii/S2352550923002634 (Accessed 20 January 2024).

Still, we face far more questions than answers in this new space; hence the need for a climate robotics network, conceptual framework, research agenda, series of white papers, summit, and knowledge base. Some of the leading questions we seek to address as a community include:

Uses Cases

- Which Climate Solutions are best scaled with robotics?
- What novel solutions can robotics bring to Climate Action?
- When does applying robotics for Climate Action make no sense?
- What are the early deployment best practices and lessons learned?

Inclusion and Impact

- How do we enable inclusion in the design and deployment of climate robotics?
- How do we ensure diversity, equity, and inclusion in climate robotics?
- Can robotics have a greater impact on climate adaptation or mitigation?
- How do we expand the space for locally-led action in climate robotics?

Enabling Environment

- How do we incentivize the development of simple, low-cost solutions?
- What advances in robotics are essential for Climate Action?
- What are the different funding instruments needed to finance climate robotics solutions?
- What are the skillsets and correct team composition for effective Climate Robotics?

Challenges

- What are the risks and dangers of deploying climate robotics?
- What does ethical, responsible, and sustainable climate robotics look like?
- What existing/future barriers might prevent meaningful progress in climate robotics?
- How do we promote effective dialogue between climate experts and roboticists?
- What policy changes are necessary to enable responsible innovation?

This White Paper seeks to start an informed discussion on climate robotics and thus invites the broader community to join us on Slack to continue and expand these discussions:

https://climaterobotics.network/slack