

# Joule

Volume 3 Number 9 September 18, 2019



**CellPress**  
www.cell.com

deep mitigation pathways. *Nat. Commun.* 10, 3277.

9. Lawrence, M.G., and Schäfer, S. (2019). Promises and perils of the Paris Agreement. *Science* 364, 829–830.
10. Breyer, C., Fasihi, M., and Aghahosseini, A. (2019). Carbon Dioxide Direct Air Capture for effective Climate Change Mitigation based on Renewable Electricity: A new Type of Energy System Sector Coupling. *Mitig. Adapt. Strategies Glob. Change*. Published online February 13, 2019. <https://doi.org/10.1007/s11027-019-9847-y>.
11. Vartiainen, E., Masson, G., Breyer, C., Moser, D., and Medina, E.R. (2019). Impact of Weighted Average Cost of Capital, Capital Expenditure, and Other Parameters on Future Utility-Scale PV Levelised Cost of Electricity. *Prog. Photovolt. Res. Appl.* Published online August 29, 2019. <https://doi.org/10.1002/ppp.3189>.
12. Gunnarsson, I., Aradóttir, E.S., Oelkers, E.H., Clark, D.E., Arnarson, M.I., Sigfusson, B., Snæbjörnsdóttir, S.O., Matter, J.M., Stute, M., Juliusson, B.M., et al. (2018). The rapid and cost-effective capture and subsurface mineral storage of carbon and sulfur at the CarbFix2 site. *Int. J. Greenh. Gas Control* 79, 117–126.
13. Creutzig, F. (2016). Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *Glob. Change Biol. Bioenergy* 8, 4–10.
14. Nemet, G.F. (2019). *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation* (Routledge).
15. Chen, C., and Tavoni, M. (2013). Direct air capture of CO<sub>2</sub> and climate stabilization: a model based assessment. *Clim. Change* 118, 59–72.
16. Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., Bertram, C., de Boer, H.-S., Fragkos, P., Fujimori, S., et al. (2019). Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* 172, 1254–1267.
17. van der Giesen, C., Meinrenken, C.J., Kleijn, R., Sprecher, B., Lackner, K.S., and Kramer, G.J. (2017). A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO<sub>2</sub> versus MEA-Based Postcombustion Capture. *Environ. Sci. Technol.* 51, 1024–1034.
18. Hansen, J., Sata, M., Kharecha, P., von Schuckmann, K., Beerling, D.J., Cao, J., Marcott, S., Masson-Delmotte, V., Prather, M.J., Rohling, E.J., et al. (2017). Young people's burden: requirement of negative CO<sub>2</sub> emissions. *Earth System Dynamics* 8, 577–616.

<sup>1</sup>LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finland

<sup>2</sup>Soletair Power Oy, Tuotantokatu 2, 53850 Lappeenranta, Finland

<sup>3</sup>Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 19, 10829 Berlin, Germany

<sup>4</sup>Technical University Berlin, Chair Sustainability Economics of Human Settlements, Straße des 17. Junis 135, 10623 Berlin, Germany

\*Correspondence: [christian.breyer@lut.fi](mailto:christian.breyer@lut.fi)  
<https://doi.org/10.1016/j.joule.2019.08.010>

## COMMENTARY

# Tackling Climate Change through Radiative Cooling

Jeremy N. Munday<sup>1,\*</sup>



Jeremy Munday is currently an associate professor at the University of Maryland, College Park, and his work focuses on demonstrating new technologies based on novel physics and engineering. He received his PhD from Harvard University in 2008 and was a postdoctoral scholar at Caltech prior to his appointment at Maryland. Dr. Munday is the recipient of several awards including the DARPA Young Faculty Award, NSF CAREER Award, ONR YIP Award, the OSA Adolph Lomb Medal, the IEEE Photonics Society Young Investigator Award, the SPIE Early Career Achievement Award, and the NASA Early Career Faculty Space Technology Research Award.

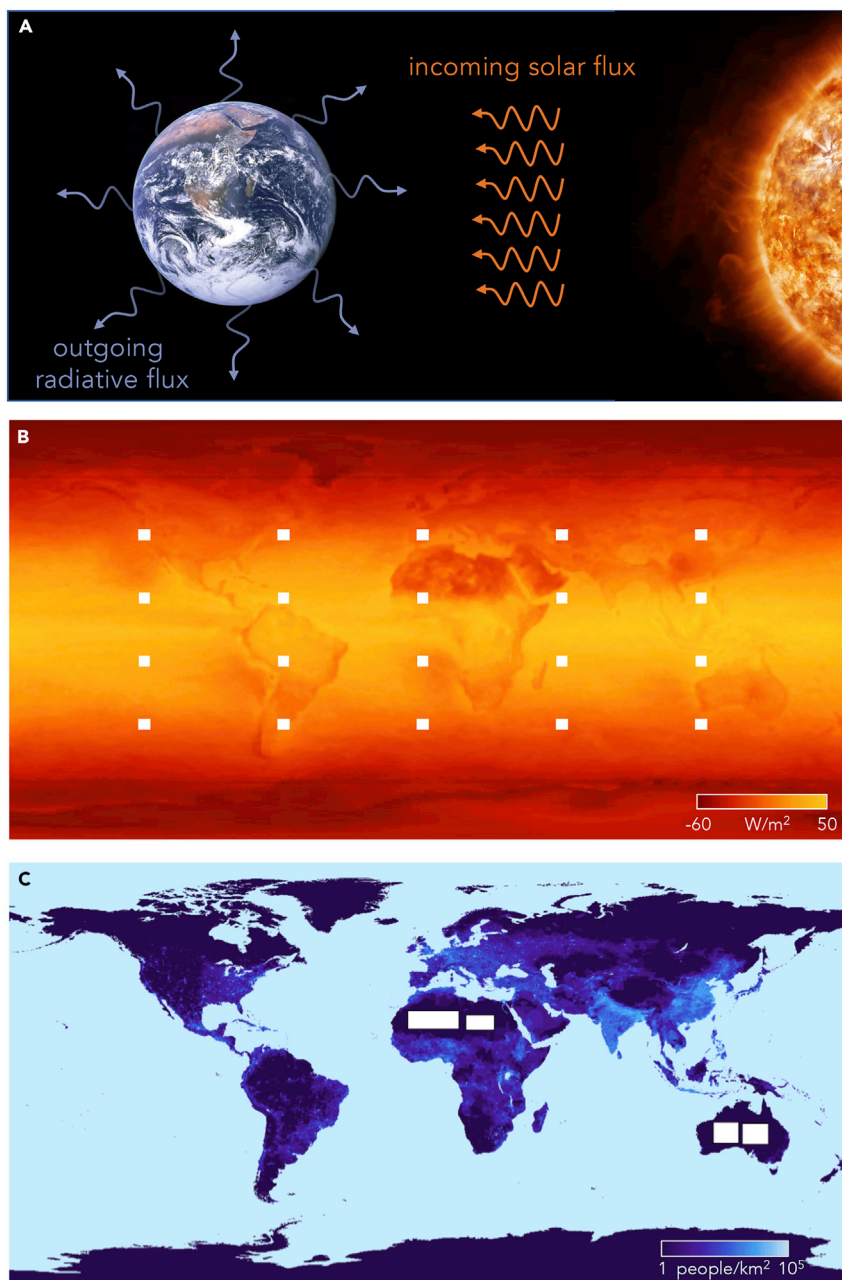
Despite growing public concerns and international agreements, few concrete actions have been taken to fix

our changing climate. In fact, the Earth is now warming faster than expected, and greenhouse gas emissions are still on the rise. The path forward has been clear: a reduction in CO<sub>2</sub> emission is needed through an increase in energy efficiency and cleaner power production. However, failure to act is making these solutions harder to realize, because the CO<sub>2</sub> that we put in the atmosphere today can persist for decades. The Earth has already warmed by 1°C above pre-industrial levels and is expected to reach 1.5°C in the next 10 to 20 years.<sup>1,2</sup> With time running out, we may need to turn to additional mitigation strategies.

One dramatic option is climatic geoengineering, where humans deliberately intervene to help force the Earth's climate in a particular direction. This concept usually takes on one of two routes: (1) capture and store the current atmospheric greenhouse gases or (2) reduce the amount of solar illumination absorbed by the Earth. While neither of these options address the core problem that our energy economy is driven by fossil fuels, there are a number of research groups pursuing them, especially the question of large-scale, economically feasible CO<sub>2</sub> capture and sequestration. The second option has been more controversial, and perhaps for good reason. A reduction in solar absorption is usually proposed through the injection of reflective aerosols into the atmosphere; however, serious concerns have been raised regarding side effects of these forms of geoengineering and our ability to undo any of the climatic changes we create. Other options including increasing reflectivity by painting roofs white or deploying giant reflective surfaces in space, although the increased reflectivity likely falls short of what is needed and comes at a high financial cost.

As an alternative geoengineering approach, we consider increasing the radiative heat emission from the Earth





**Figure 1. A Delicate Balance of Heat Flow Determines the Earth's Temperature**

(A) Incoming radiation from the sun heats the Earth, while the emission from the Earth causes cooling.

(B) Net radiation (incoming from the sun and outgoing from the Earth) for 2017 from monthly averages.<sup>3</sup> If an area of the Earth equivalent to the regions depicted by white rectangles (total area of  $5 \times 10^{12} \text{ m}^2$ ) were covered by currently available radiatively emitting surfaces, the total global heat flux could be reduced by nearly  $1 \text{ W/m}^2$ , potentially enough to stop the increase of global temperatures.

(C) Population density map.<sup>4</sup> White rectangles represent four desert regions with populations densities  $< 1 \text{ person/km}^2$  and a total area of  $5 \times 10^{12} \text{ m}^2$  (same as in B). The actual implementation of this strategy would be broken into several smaller regions globally rather than the white boxes depicted in (B) and (C), which are shown for simplicity.

rather than merely decreasing its solar absorption (Figure 1). Radiative heat from the sun is absorbed by the Earth and heats it. Simultaneously, the Earth emits heat to space and cools. When the incoming heat is balanced by the outgoing heat, the Earth reaches a stable, steady-state temperature. Currently the Earth is absorbing  $\sim 1 \text{ W/m}^2$  more than it is emitting,<sup>5</sup> which leads to an overall warming of the climate. By covering the Earth with a small fraction of thermally emitting materials, the heat flow away from the Earth can be increased, and the net radiative flux can be reduced to zero (or even made negative), thus stabilizing (or cooling) the Earth.

Over the last few years, researchers have developed thermally emissive materials that can radiate  $\sim 100 \text{ W/m}^2$  out to space through the atmospheric transparency window.<sup>6–10</sup> The idea is to make a material that is reflective to the sunlight, yet emissive to the wavelength range of  $8\text{--}20 \mu\text{m}$ . In doing so, no solar radiation is absorbed, and only radiative cooling occurs (during both day and night). These materials can be printed roll-to-roll or deposited as a paint.<sup>8,9</sup> If only 1%–2% of the Earth's surface were instead made to radiate at this rate rather than its current average value, the total heat fluxes into and away from the entire Earth would be balanced and warming would cease.

As a simplified example of how this concept might work, we first consider what land resources it would take to implement. To offset  $1 \text{ W/m}^2$  globally, we need approximately  $5 \times 10^{12} \text{ m}^2$  of surface coverage with  $100 \text{ W/m}^2$  radiative emitters (the exact needs will depend on where the emitters are placed and what original flux they offset). If used as one continuous area, it corresponds to a little more than half the size of the Sahara Desert. Ideally this area would be broken into several small regions globally (including roofs and other sky-facing surfaces). For

illustrative purposes only, we consider two simple distributions to get a better sense of the areas involved. First, we show 20 equal area regions distributed evenly across the Earth (Figure 1B). This distribution covers both land and sea as well as populated and unpopulated areas. Next, we consider the case of land masses with a population density  $< 1$  person/km<sup>2</sup> and those that represent desert climates to facilitate clear/dry environments that are most conducive to radiative transfer (note: some deserts naturally promote radiative emission and the total land requirement and effectiveness of the radiative coolers will depend on this value). For this case (Figure 1C), we divided the same total area into only four sub-areas and distributed them across the Sahara and Australian deserts. The actual radiative flux of the emitters will also be dependent on local weather conditions (including temperature, humidity, and cloud cover) and will vary by season and specific global position, requiring potentially larger or smaller areal coverage to meet a particular radiative flux goal. All of these factors will need to be considered when choosing the actual area distribution.

Next, we consider the potential costs. Large-scale polymer sheets are commercially available for  $< \$0.25/\text{m}^2$ , and roll-to-roll processing of radiative films has been estimated at \$0.25 to \$0.50 per square meter,<sup>11</sup> or \$1.25 to \$2.5 trillion for the total area we considered (although significant price reductions are conceivable at this scale). This cost corresponds to about 10% of US GDP or 3% of global GDP and is a small investment compared to the estimated \$20 trillion global benefits predicted by limiting global warming to 1.5°C rather than 2°C.<sup>12</sup> Additional encapsulation, mounting, labor, etc. would increase the total costs; however, the polymer itself could be used for support,<sup>8</sup> or alternative versions involving paint-like processes<sup>9</sup> could be used at potentially lower costs.

Further studies are also needed to understand degradation processes and potential maintenance in these newly developed materials.

Despite the potential benefits and promise, we should proceed with caution when trying to engineer the global climate. Large cooling structures could also lead to uneven temperature variations that may result in further climatic and environmental changes on a variety of length scales that would need to be studied. There are also many land use issues given the large areas involved, ranging from property rights to environmental concerns for local flora and fauna. Unexpected effects will likely occur, but fortunately, these structures can be removed immediately if needed, unlike methods that involve dispersing particulate matter into the atmosphere, which can last for decades. Further, radiative cooling cannot be a complete, standalone solution, but rather is part of a more comprehensive approach that must include CO<sub>2</sub> reduction. Otherwise, the radiative balance will not last long, and the potential financial benefits of mitigation will not fully be realized because of continued ocean acidification, air pollution, and redistribution of biomass.

We note that the simple analysis presented here is merely a first step showing the potential of such an approach and further detailed techno-economic analysis is needed. Unlike mature sky-facing technologies such as photovoltaics, the preferred embodiment of the radiative emitter is still a work in progress and needs further development before any accurate cost models can be determined. The spectral dependence of the emitter must also be carefully designed to ensure that the emission is *through* the atmospheric transparency window and out to space, rather than just to the atmosphere, which would allow for local but not global cooling.

Similarly, research is needed into the yearly averaged radiative heat flux for emitters at different locations and how the resulting changes in weather patterns may influence emission. To move forward, physicists and engineers working on photonic engineering of radiative emitters can learn from techniques and analysis within the photovoltaics community while simultaneously collaborating with climate scientists, environmental engineers, and policy makers to help determine the potential global impact of such strategies.

Mitigating climate change is a tall task, and we are reaching a point where all options should be on the table.

1. Xu, Y., Ramanathan, V., and Victor, D.G. (2018). Global warming will happen faster than we think. *Nature* 564, 30–32.
2. Intergovernmental Panel on Climate Change (2018). Global Warming of 1.5 °C (IPCC).
3. Net radiation from NASA Earth Observations available at: [https://neo.sci.gsfc.nasa.gov/view.php?datasetId=CERES\\_NETFLUX\\_M](https://neo.sci.gsfc.nasa.gov/view.php?datasetId=CERES_NETFLUX_M).
4. Gridded Population of the World dataset, Version 3 (GPWv3), available from NASA Earth Observations available at: [https://neo.sci.gsfc.nasa.gov/view.php?datasetId=SEDAC\\_POP](https://neo.sci.gsfc.nasa.gov/view.php?datasetId=SEDAC_POP).
5. Stephens, G.L., Li, J., Wild, M., Clayson, C.A., Loeb, N., Kato, S., L'Ecuyer, T., Stackhouse, P.W., Jr., Lebsock, M., and Andrews, T. (2012). An update on Earth's energy balance in light of the latest global observations. *Nat. Geosci.* 5, 691–696.
6. Fan, S. (2017). Thermal Photonics and Energy Applications. *Joule* 1, 264–273.
7. Raman, A.P., Anoma, M.A., Zhu, L., Rephaeli, E., and Fan, S. (2014). Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* 515, 540–544.
8. Zhai, Y., Ma, Y., David, S.N., Zhao, D., Lou, R., Tan, G., Yang, R., and Yin, X. (2017). Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science* 355, 1062–1066.
9. Mandal, J., Fu, Y., Overvig, A.C., Jia, M., Sun, K., Shi, N.N., Zhou, H., Xiao, X., Yu, N., and Yang, Y. (2018). Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. *Science* 362, 315–319.

10. Zhao, D., Aili, A., Zhai, Y., Lu, J., Kidd, D., Tan, G., and Yin, X. (2018). Subambient Cooling of Water: Toward Real-World Applications of Daytime Radiative Cooling. *Joule* 3, 111–123.
11. Service, R.F. (2017). Cheap plastic film cools whatever it touches up to 10°C. *Science*. Published online February 9, 2017. <https://doi.org/10.1126/science.aal0732>.
12. Burke, M., Davis, W.M., and Diffenbaugh, N.S. (2018). Large potential reduction in economic damages under UN mitigation targets. *Nature* 557, 549–553.

<sup>1</sup>Department of Electrical and Computer Engineering and the Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD 20742-3511, USA

\*Correspondence: [jnmunday@umd.edu](mailto:jnmunday@umd.edu)  
<https://doi.org/10.1016/j.joule.2019.07.010>

#### COMMENTARY

## Meeting U.S. Solid Oxide Fuel Cell Targets

**Michael M. Whiston,<sup>1</sup>**  
**Inês M.L. Azevedo,<sup>2</sup>**  
**Shawn Litster,<sup>3</sup>**  
**Constantine Samaras,<sup>4</sup>**  
**Kate S. Whitefoot,<sup>1,3</sup>**  
**and Jay F. Whitacre<sup>1,5,6,\*</sup>**

Michael M. Whiston is a Postdoctoral Research Associate in the Department of Engineering and Public Policy at Carnegie Mellon University. As a postdoctoral researcher, Michael has elicited the assessments of over 100 fuel cell experts and presented his findings on Capitol Hill and at international conferences. Michael has published research in the *Proceedings of the National Academy of Sciences*, *Journal of Power Sources*, and *Journal of Fuel Cell Science and Technology*. Michael received his Ph.D. from the University of Pittsburgh in Mechanical Engineering. During his graduate work, Michael performed cost analyses of SOFC systems and developed a dynamic SOFC model.

Professor Inês M.L. Azevedo is an Associate Professor of Energy Resources En-

gineering at Stanford University. Her work focuses on the transitions to sustainable and low-carbon energy systems. She has published 70+ journal publications and graduated 26 Ph.D. students. Since 2010, she has been serving as PI/co-PI of the NSF sponsored Climate and Energy Decision Making Center (CEDM). Professor Azevedo participated as a committee member and co-author on several reports from the U.S. National Academy of Sciences. She was awarded the “40 Scientists under 40” award by the World Economic Forum (WEF) (2014) and the C3E Research Award for Women in Energy (2017).

Shawn Litster is a Professor in the Department of Mechanical Engineering at Carnegie Mellon University in Pittsburgh, PA. He received his Ph.D. in Mechanical Engineering from Stanford University and his bachelor’s and master’s degrees from the University of Victoria in Canada. His current research focus is micro- and nano-scale transport phenomena in energy conversion technologies where electrochemistry and electrokinetics play a dominant role, including fuel cells, batteries, and ultra-capacitors. He is the author of over 60 journal publications on fuel cells and batteries.

Constantine Samaras is an Associate Professor of Civil and Environmental Engineering and a Fellow in the Wilton E. Scott Institute for Energy Innovation at Carnegie Mellon University. His research spans energy, automation, and climate change. He has contributed to U.S. National Academies of Sciences reports, the Fourth National Climate Assessment, and the Global Energy Assessment. He received a Ph.D. in Civil and Environmental Engineering and Engineering and Public Policy from Carnegie Mellon University and a M.P.A. in Public Policy from New York University. He was named 2018 Professor of the Year by the American Society of Civil Engineers Pittsburgh Section.

Kate S. Whitefoot is an Assistant Professor of Engineering and Public Policy and of Mechanical Engineering at Carnegie Mellon University. Professor Whitefoot’s research bridges engineering design theory and analysis with that of economics to understand how product and process design affects enterprise and social-welfare objectives, such as expected profits, customer adoption, productivity, energy efficiency, emissions, and consumer welfare. Her work is featured in the *Wall Street Journal*, *Washington Post*, *Popular Mechanics*, and *Bloomberg Business* and referenced in the 2017–2025 Corporate Average Fuel Economy rulemaking.

Professor Jay F. Whitacre started his career at the California Institute of Technology/Jet Propulsion Laboratory. Since joining Carnegie Mellon University in 2007, Dr. Whitacre has focused on the synergistic fields of energy storage and energy system techno-economic assessment. He has developed a novel battery chemistry/design that is manufactured and sold by Aquion Energy, a company he founded in 2008. He is the recipient of multiple awards, including the 2017 Leigh Ann Conn Prize for Renewable Energy, the 2015 Lemelson-MIT Prize, and the 2014 Caltech Resnick Institute Resonate Award, and has been named a Fellow of the National Academy of Inventors.

#### Introduction

Solid oxide fuel cells (SOFCs) are highly efficient, scalable, high-temperature (typically greater than 600°C), solid-state devices that, through an electrochemical reaction, convert hydrocarbon or hydrogen fuels into electricity and thermal energy. Without compromising efficiency, SOFCs can be connected, and interconnects electrically joined, to form stacks that meet demand. Commercial SOFC systems are capable of operating on hydrogen, natural gas, propane, and

