Columbia World Projects
Decarbonization Forum Report

February 28, 2020

Foreword

Dear Reader,

On behalf of Columbia World Projects (CWP), we are pleased to present the following report on our Forum on Decarbonization, one of an ongoing series of meetings dedicated to bringing together academia with partners from government, non-governmental and intergovernmental organizations, the media, and the private sector to identify projects designed to tackle fundamental global challenges and improve people's lives.

Climate change represents one of the most urgent and extensive global threats confronting us today. With each year, greenhouse gas emissions continue to climb, warming the Earth and exacting devastating consequences on both natural and built environments. Rising sea levels and extreme weather events are more frequently leading to crises in almost every domain, including food security, biodiversity, public health, and national security in every region of the world. While the 2015 Paris Agreement resulted in a near universal commitment by countries to limit the increase in average global temperature to below 2°C and to "pursue efforts" to limit the increase to 1.5°C, neither goal is likely to be achieved based on current trends.

On September 17, 2019, CWP invited approximately 35 experts from a range of fields and disciplines to take part in a Forum, in order to both deepen our understanding of the challenge and propose concrete ways of catalyzing action to address it. In seeking ideas that could have a concrete impact, we focused not only on ways to reduce greenhouse gas emissions, but also on developing and implementing technologies for carbon capture and storage. The attached report describes the work that took place at the Forum and identifies six promising project ideas for possible further development by CWP. We anticipate many of the remaining proposals will be pursued through other channels or partnerships that emerge from the Forum.

We chose to focus on decarbonization because it is an abiding challenge in need of urgent, coordinated action, and because it is an issue where we believe university expertise and capabilities can have significant impact. It is also a challenge that shapes nearly every dimension of human life, and so, invariably, solutions will require engagement by a range of experts and institutions. We hope the innovative proposals and insights shared in this report will contribute to the broader conversation around how best to tackle this global challenge.

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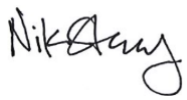

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I. Defining the Challenge

Global warming is widely recognized as one of the greatest threats facing humanity, and it is getting worse. Each year, the United Nations Environment Programme (UNEP) takes stock of the rising level of global greenhouse gas (GHG) emissions, comparing them to where they need to be to avert catastrophic climate effects. This "emissions gap" contributes to the escalating heat waves, droughts, and extreme storms in communities around the world, with devastating consequences for human development in every region. Yet despite the attention this issue has received, the emissions gap is increasing significantly.[1] Nine of the 10 warmest years on record have occurred since 2005. Concentrations of carbon dioxide (CO_2) – the leading heat-trapping gas – are higher than they have been at any time in human history. Global greenhouse gas emissions continue to climb, increasing roughly 1.7 percent in 2018, with China as the leading emitter of energy-related CO_2, followed by India and the United States.[2]

At the 2015 United Nations climate negotiations in Paris, countries agreed to limit the global average temperature increase since the Industrial Revolution to well below 2°C and to "pursue efforts" to limit the temperature increase to 1.5°C. Leaders of small island nations with low-lying coastal areas, like the Marshall Islands and Maldives, view the 1.5°C goal as critical to their survival; yet, at this point, neither goal appears likely to be met. Based on the latest information on countries' climate commitments and their projected emissions pathways, the UN World Meteorological Organization predicts the average temperature increase will be between 3°C and 5°C by 2100.[3] Even an increase at the lower end of that range will have a devastating effect on humanity. If there is any hope to meet the benchmarks set out in the Paris Agreement and cap the average global temperature increase, a multi-pronged strategy of deep decarbonization – one that both achieves net zero GHG emissions and removes existing carbon from Earth's atmosphere – will need to be implemented.

The sheer impact of climate change across multiple fields and spheres of life speaks to the complexity of addressing the challenge. Geophysical features of the Earth are being reshaped: the ocean is rising and eroding coastlines; the boundary lines of the tropics are heading toward the North and South Pole at about 30 miles per decade; the line of aridity defining the American West has moved roughly 140 miles east since 1980; and while the Sahara Desert is getting larger, the sea ice in the Arctic is disappearing.[4] Almost a year ago, the U.S. National

[1] United Nations Environmental Programme, *Emissions Gap Report 2018*, November 2018, https://www.unenvironment.org/resources/emissions-gap-report-2018, p. 4.

[2] According to the International Energy Agency, energy related CO_2 emissions rose by 1.7 percent to 33.1 billion tonnes from the previous year, the highest rate of growth since 2013, while U.S. CO_2 emissions grew by 3.1 percent in 2018, reversing a decline a year earlier. China grew by 2.5 percent and India by 4.8 percent. China, India, and the United States account for 85 percent of the net increase in emissions. IEA, *Global Energy & CO2 Status Report*, accessed September 10, 2019, https://www.iea.org/geco/emissions/.

[3] "Global temperatures on track for 3-5 degree rise by 2100: U.N." *Reuters*, November 28, 2018, https://www.reuters.com/article/us-climate-change-un/global-temperatures-on-track-for-3-5-degree-rise-by-2100-u-n-idUSKCN1NY186.

[4] NASA, "Is it too late to prevent climate change?" Global Climate Change: Vital Signs of the Planet, accessed, last modified August 28, 2019, https://climate.nasa.gov/faq/16/is-it-too-late-to-prevent-climate-change/; Nicola Jones, "Redrawing the Map: How the World's Climate Zones are Shifting," Yale Environment 360, October 23, 2018, https://e360.yale.edu/features/redrawing-the-map-how-the-worlds-climate-zones-are-shifting; Richard Seager et al., "Whither the 100th Meridian? The Once and Future Physical and Human Geography of America's

Climate Assessment was released. The report, which the U.S. Congress mandates every four years and is produced by 13 federal agencies, traces the effects of climate change on every region of the United States. Its findings were devastating – making clear that no one will remain immune from the impact of our current trajectory. Depending on the region, Americans will experience an additional month or two of days above 37.78°C/100°F. Warming has increased the wildfire season by 80 days in some places, and by the year 2100, annual acreage burned could increase by as much as six times current rates. Sea levels have already risen three inches since 1990 and seven to eight inches since 1900. Even with adaptation measures, the report indicated that climate change carries with it significant economic costs. It is easy to imagine how the findings of this report reflect what is likely to happen in other countries around the world.

Against this backdrop, Forum participants representing a range of institutions and areas of expertise related to climate change reflected on the need for collective action at a scale commensurate with the threat posed and recommended focusing the discussion on projects that could plausibly be scaled to have a substantial impact on global warming. At the same time, several participants expressed the view that the changes needed to properly implement and effectively scale many of the proposed projects in order to have such impact would require what one participant called a "transformational disruption" to our societies. As another participant noted, there is no way to force the adoption of necessary policies; as such, several participants talked about the need to change the landscape within which the various projects would be implemented, suggesting that it would be useful to think through, for example, how to effect desirable cultural shifts informed by ethical decision-making on climate, and how to build new market incentives to promote decarbonization into economies. Relatedly, as described in further detail below, multiple participants pointed to the immense social and economic ramifications of adequately responding to the climate crisis, shedding light on the complexity of implementing the transformative, disruptive policies and practices that are necessary to change the world in a short period of time, without reinforcing or exacerbating the unacceptable inequities that currently exist in our societies. Finally, participants underscored the importance of taking into account all gases that contribute to the greenhouse effect, in particular methane, rather than limiting the discussion to CO_2 alone.[5]

Political, economic, and social costs of climate change

Several Forum participants took note of the varying and multi-faceted costs that global warming imposes on countries, communities, and individuals. While most people tend to think of warming, extreme weather events, and rising sea levels as the chief consequences of climate change, there is a growing recognition and effort to measure the impact of climate change in other fields, including national security, health, and geopolitics. For example, a 2018 World Bank report indicated that by 2050, if no action is taken, there will be more than 143 million

Arid–Humid Divide. Part I: The Story So Far," *Earth Interactions* 22, no. 5 (March 2018): 1–22, https://doi.org/10.1175/EI-D-17-0011.1.

[5] Although the focus of the Forum, as indicated in materials prepared for the meeting, was on all gases that contribute to the greenhouse effect, including methane, nitrous oxide, and chlorofluorocarbons, the vast majority of the attention goes to carbon dioxide.

internal climate migrants across Sub-Saharan Africa, South Asia, and Latin America.[6] These are people who will migrate from areas with lower water availability and crop productivity, as well as from areas affected by rising sea levels and storm surges. UNESCO, among others, has reported on how global warming has further destabilized already vulnerable regions, like the Horn of Africa.[7] The stresses on natural resources undermine the capacity of nations to govern themselves and increase the likelihood of conflict, particularly as they threaten the foundational resources that people and nations rely on for survival, security, and prosperity. Moreover, it is impossible to effectively assess the impact of climate change on individual sectors such as food, water, and migration separately; one must consider the interactions among these sectors and the consequences of such interactions in order to truly understand the breadth of the impact.

Efforts to estimate the financial costs associated with climate change have been challenging, but doing so is critical to demonstrating not only the current damage being done, but also the future costs of inaction. Moreover, as one Forum participant noted, estimating such costs can at the very least help to spur changes in the market, if not elsewhere in our societies. The economic costs of climate change include increased cooling costs for buildings; damage from additional extreme weather events, sometimes caused and sometimes exacerbated by climate change; the diminished yield of crops and dairies as a result of heat stress; the lower productivity of fishery industries due to ocean warming and acidification; the burden on public infrastructure of rising sea levels; the rising health care costs associated with more frequent, longer, or more intense heat waves and the spread of tropical diseases into new climate zones; the loss of coral reefs and other marine ecosystems that support food supply chains; and the decline of freshwater supplies as glaciers melt and winter snows are diminished. More than 200 of the world's largest listed companies representing nearly $17 trillion in market capitalization forecasted this year that climate change could cost them a combined total of almost $1 trillion over the next five years.[8] The World Bank has projected costs of hundreds of billions of dollars as a consequence of the impact of climate change on health, the world's food supply, and weather leading to extreme natural disasters.[9]

In the context of regulating CO_2 emissions in the United States, federal agencies established a metric known as the social cost of carbon (SCC), which helps analysts assess the economic benefits of climate action and the economic costs of inaction by assigning a dollar value to the benefit of reducing CO_2 emissions. Estimates of the SCC vary significantly: in 2016, the Obama administration projected that, after adjusting for inflation, each ton of CO_2 emitted in 2020 would cause roughly $50 in total damages, while other experts have estimated that costs should be closer to $200 per metric ton today; meanwhile, the Trump administration has projected

[6] "Groundswell: Preparing for Internal Climate Migration," The World Bank, March 19, 2018, https://www.worldbank.org/en/news/infographic/2018/03/19/groundswell---preparing-for-internal-climate-migration.

[7] Caitlin E. Werrell and Francesco Femia, "Climate change raises conflict concerns," *The UNESCO Courier*, 2018-2, https://en.unesco.org/courier/2018-2/climate-change-raises-conflict-concerns.

[8] United Nations Climate Change, "Major Companies Face USD 1 Trillion in Climate Risks," June 4, 2019, https://unfccc.int/news/major-companies-face-usd-1-trillion-in-climate-risks; See also Climate Disclosure Project, "World's biggest companies face $1 trillion in climate change risks," June 4, 2019, https://www.cdp.net/en/articles/media/worlds-biggest-companies-face-1-trillion-in-climate-change-risks.

[9] The World Bank, "Climate Change," last updated April 2, 2019, https://www.worldbank.org/en/topic/climatechange/overview.

much lower costs.[10] What is clear is that the economic benefits of reducing CO_2 emissions are substantial, while the already massive costs of complacency continue to grow.[11]

A number of participants took a more humanist view of the social costs of addressing climate change and highlighted the importance of equity in shaping decisions about mitigation and adaptation. They noted that the populations and countries that are suffering the most harm from global warming are disproportionately the poor and vulnerable,[12] and consequently those constituencies with the greatest motivation to address the problem also tend to have the least political power to make change. In fact, some low-income countries contend they are unfairly being asked to make changes to their patterns of energy consumption that middle- and high-income countries were not asked to make in their own periods of rapid industrialization. Such concessions, they argue, will hamper economic growth and undermine their ability to deliver energy access to all their people – a key enabler of opportunity and development. At a societal level, some of these same populations are also likely to face economic dislocation in the transition to green economies, underscoring the importance of planning for worker transitions and investing in job training initiatives.

Addressing climate change requires investment and innovation

Forum participants also spoke to the need for innovative negative-emission technologies along with unconventional policies and strategic investments in order to move the needle on global warming. For example, participants remarked that limiting warming to 1.5°C would imply attaining net zero CO_2 emissions globally by 2050, and to do so it would be necessary to undertake a wide range of measures targeting the largest emitters to reduce emissions, including deep reductions in non-CO_2 drivers such as methane; electrifying buildings and transport; capping emissions on industrial manufacturing; achieving significant reductions in energy demand; and implementing policies to reflect a high price on emissions through carbon pricing, performance standards, and alternative measures.[13] Yet, as others noted, even those

[10] Robert S. Pindyck, "The Social Cost of Carbon Revisited," NBER Working Paper No. 22807 (November 2016): https://www.nber.org/papers/w22807.pdf; Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," August 2016, https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf; and Brad Plumer, "Trump Put a Low Cost on Carbon Emissions. Here's Why It Matters," *New York Times*, August 23, 2018, https://www.nytimes.com/2018/08/23/climate/social-cost-carbon.html.

[11] To cite just one example, the U.S. Department of Agriculture studied the impact of heat stress produced by climate change on the productivity of U.S. dairies and found that in 2010 alone, the U.S. dairy industry lost $1.2 billion in production.

[12] Without urgent action, according to a World Bank report, climate impacts could push an additional 100 million people into poverty by 2030. The World Bank, *Shock Waves: Managing the Impacts of Climate Change on Policy*, November 2015, https://openknowledge.worldbank.org/bitstream/handle/10986/22787/9781464806735.pdf. Additionally, a 2017 study found that the poorest 100 counties in the United States are projected to suffer an average loss of 11 percent of their GDP due to climate change, while the richest 100 counties are projected to lose just 1 percent of their GDP. The research demonstrates how climate change will exacerbate existing inequities in our societies. Solomon Hsiang et al., "Estimating economic damage from climate change in the United States," *Science*, Vol. 356, Issue 6345 (June 2017): https://science.sciencemag.org/content/356/6345/1362.

[13] Even if countries were, however, to bring their emissions in line with national pledges under the Paris Agreement, which few counties are on track to do, emissions would have to decline to zero by approximately 2075 to stay below a 2°C increase, which the world is not on track to do on its current trajectory.

actions will not be enough to avoid catastrophic consequences. According to a report from the Intergovernmental Panel on Climate Change (IPCC), "pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of CO_2 removal (CDR) measures, which are uncertain and entail clear risks."[14] Thus, limiting warming to 1.5°C would essentially demand a fundamental shift in priorities and policymaking around CO_2 removal and a commitment to eliminate gigatons of CO_2 from the Earth's atmosphere every year. This underscores the critical importance of simultaneously pursuing breakthroughs in cost-effective technologies that result in negative carbon emissions, as well as in carbon capture and storage.[15] Such innovation, in addition to requiring robust political support, will require a substantial investment.

Mobilization across society is necessary to spur political will

Several participants noted that the impasse on achieving decarbonization is exacerbated by confusion and ineffective messaging about how best to address the problem, driven in part by social and political divisions around climate change and its causes. This is true in the United States and many other parts of the world, where powerful lobbies continue to push back against significant changes that they see as cutting against their interests. Indeed, as one participant noted, we are at a critical juncture where the difference between pursuing transformative action or staying mired in inaction will depend on whether we cling to the fault lines that increasingly define the current political landscape, which are fueled by division and fear, or whether we instead choose to embrace a "politics of solidarity" in the face of a shared existential threat. The effort to increase awareness about climate change and persuade individuals and communities to make changes that can mitigate global warming has been met by a forceful resistance – one that often seeks to mobilize opposition along lines of class, tribe, nationality, or other means, and to stoke fear and resentment toward collective efforts.

Ultimately, the public and private sectors – and everyday citizens – will need to generate the political will to catalyze ambitious efforts to address climate change at scale. Despite near universal ratification of the Paris Agreement, the presence of that will – and the scope and pace of decarbonization – is hardly uniform. Some governments, such as Norway, Denmark, and Chile, are leading a transition to clean energy systems and pursuing efforts to decarbonize whole sectors of their economies. Other governments, however, are stalled or even curtailing efforts to mitigate climate change, as was recently demonstrated when the Trump Administration announced plans to roll back federal requirements that have reduced methane emissions by oil and gas companies,[16] or in its proposal to lift restrictions on logging in more than half of the 16.7-million-acre Tongass National Forest in Alaska, the world's largest intact temperate rainforest.[17] Facing such intransigence at the national level in the United States,

[14] United Nations Intergovernmental Panel on Climate Change, *Global Warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (October 2018): https://www.ipcc.ch/sr15/, p. 95.

[15] *Ibid.*, 17.

[16] Lisa Friedman and Coral Davenport, "Curbs on Methane, Potent Greenhouse Gas, to Be Relaxed in U.S," *New York Times*, August 30, 2019, https://www.nytimes.com/2019/08/29/climate/epa-methane-greenhouse-gas.html.

[17] Juliet Eilperin, "Trump administration proposes expanding logging in Alaska's Tongass National Forest," *Washington Post*, October 15, 2019, https://www.washingtonpost.com/climate-environment/trump-

many state and municipal governments have taken the mantle of leadership on climate change, as have universities and civil society, continuing to drive innovation around implementing low-carbon energy and carbon removal technologies.

To be sure, it is difficult to achieve broad-based mobilization against a threat that is devastating in the aggregate but is often perceived as a relatively minor threat in the lives of individuals. Additionally, for many people, the impact that climate change has on their lives is not attributed directly or exclusively to rising temperatures, making its consequences appear less direct, and thus less urgent. What's more, our societies and governments have demonstrated a poor track record when it comes to addressing problems that future generations will have to bear – even massive, existential problems – as opposed to problems that are seen as needing imminent solutions. A number of participants agreed that overcoming this impasse requires a new narrative around our approach to climate change, built on a politics of solidarity that recognizes our collective vulnerability to further temperature increases, as well as our shared responsibility to each other and to future generations. But, somewhat paradoxically, it is also clear from the variation in national and community-led strategies, and even in personal biases, that a diversity of responses is not only inevitable, but necessary.

In examining each of the project proposals, participants ultimately concluded that the working groups should give thought to the cultural, political, and market shifts that would support their implementation and scaling, in an effort to consider not just their plausibility, but also whether additional action might not be taken in these realms to increase the likelihood of success.

The university has a unique role to play in decarbonization efforts

Almost every participant noted that academic institutions have a critical role to play in addressing climate change and that, furthermore, in reviewing potential projects, it would be important to consider which projects would take the greatest advantage of the unique contributions that a university can make to such efforts. Several participants were of the opinion that a project should not be chosen unless it wouldn't happen without CWP's involvement. In discussing the potential value that academia can bring in helping to address global warming, participants focused on the ability of universities to convene a multitude of stakeholders and expertise; the capacity of academia to work on long-term strategies and solutions; the extraordinary and diverse expertise that a university can bring to bear on a challenge; the credibility of the research undertaken and conclusions reached by universities, as opposed to the private sector in some circumstances; and the ability of universities to occupy a space, however limited, outside of politics.

II. Working Groups

The participants separated into five working groups, organized by themes related to the different projects that were to be reviewed by each group: (1) decarbonization of buildings; (2) breakthrough technologies in storage, materials, and capture; (3) transportation and

administration-proposes-expanding-logging-in-alaskas-tongass-national-forest/2019/10/15/92e47db8-ef77-11e9-8693-f487e46784aa_story.html.

infrastructure; (4) tracking and measuring emissions to change practice; and (5) policy innovation.

Each working group consisted of approximately eight experts, who were asked to evaluate between two and four project proposals that had been developed in advance of the Forum by participants in collaboration with CWP staff. Participants had been pre-assigned to working groups in an effort to bring together complementary fields of knowledge and distinct institutional backgrounds, while simultaneously representing different schools of thought in areas where splits exist in the expert community, with the idea of promoting a maximally effective interrogation of each project idea.

For each project proposal, the lead drafter presented a succinct summary of the idea, after which the working group's moderator facilitated a discussion aimed at providing critical feedback. Participants were asked to focus their discussion around the following questions:

- Strengths and weaknesses. In particular, are there key weaknesses, omissions, or risks in the framing of the problem or the proposed solution? How can the project be strengthened?
- Implementation challenges. What are the greatest obstacles to effectively implementing this project, and can they be overcome?
- Likely impact. If successful, what magnitude of impact will the project likely have on global warming? Is the project scalable?
- Role of the university. Do research and scholarship play a significant role in the project?

Before breaking into the working groups, the CWP Forum organizers pointed out that the groups' themes were naturally overlapping. In fact, several of the projects dealt with more than one of the themes and thus could easily have been assigned to another working group. As such, participants were asked not to limit their evaluation of assigned projects to the theme of their working group. Rather, participants were encouraged to consider how the individual projects they were evaluating were impacted by – and might help address – the themes being taken up by other working groups.

After discussing all of the individual projects, the working group members were asked to consider the strength of the project ideas reviewed by the group relative to one another, from the perspective of which projects CWP should pursue, and to summarize the main points and any recommendations they wished to make regarding each project to the plenary of Forum participants. What follows is a summary of the each of the five working groups, beginning with a discussion of the group's overarching theme, followed by a summary of each project the group discussed and the feedback it received.

1. Decarbonization of Buildings

Commercial and residential buildings account for a significant proportion of greenhouse gas emissions, and reducing their footprint is indispensable to meeting global climate targets. Nowhere is this need more acute than in cities, which are home to more than half of the world's

population and generate approximately two-thirds of the world's energy demand.[18] In New York City alone, according to a 2017 estimate, buildings produced two-thirds of the city's emissions.[19] And yet, greening buildings entails overcoming not only technological and economic challenges that range with the enormous diversity of the building stock, but also navigating the myriad institutions and actors, public and private, who have a stake in our built environment, and whose participation is critical to ensuring an effective transition. These challenges are especially pronounced for low-income communities, who would stand to benefit most from efficient buildings and efficient heating and cooling, ensuring both improved comfort and lower expenditures. Yet, the same low-income communities are rarely engaged in the design and implementation of public policies and often unable to access incentives, rebates, and other potential solutions because of their inability to shoulder the high up-front capital costs, as well as low rates of ownership. Similarly, antiquated policies can too often perversely reward inefficient investments and operations among utilities, dissuading them from investing in cost-effective, clean, and energy efficient solutions. As a result, while renewable energy accounts for 26 percent of global electricity produced, renewables provide less than 10 percent of electricity used for heating and cooling.[20] The Decarbonization of Buildings working group looked at four projects seeking pathways to decarbonize and improve energy efficiency in the building sector, with a focus on cities in the United States. The group explored the complex trade-offs that must be weighed as decisionmakers pursue such efforts, including how much to rely on gas in making the transition from oil and other fossil fuels to electrification; new incentive structures that might encourage residents and businesses to accept or even drive the transition along with certain efficiency improvements; and novel technologies that could aid in the transition. Ultimately, the group discussed how the four projects could be merged into a single effort, a summary of which follows the descriptions of the four individual projects and their feedback below.

Decarbonization of the Built Environment: The first project would involve partnering with Columbia Secondary School and at least one other entity to test three means of improving efficiency in non-residential buildings: (i) development of energy efficient building materials; (ii) direct capture of CO_2 within building systems to reduce their fresh air intake; and (iii) the use of integrated sensors and data science to improve energy efficiency. The first component – energy efficient, low-carbon construction materials – would be embedded with innovative phase change materials, which are substances that absorb and release thermal energy. These materials would be made by reacting captured anthropogenic CO_2 with solid wastes, such as fly ash from power plants and mine tailing, and thereby transform the non-structural elements of a building into a form of long-term, stable carbon storage. The second component – the direct capture of CO_2 – would be achieved by developing novel capture materials for CO_2, volatile organic compounds (VOCs), and particulates that could be integrated into existing building air filtration systems. The third component would be to directly incorporate inexpensive CO_2, VOCs, and particulate sensor systems into existing building materials – such as applying them

[18] David Roberts, "The global transition to clean energy, explained in 12 charts," *Vox*, last updated June 26, 2019, https://www.vox.com/energy-and-environment/2019/6/18/18681591/renewable-energy-china-solar-pv-jobs.

[19] Cathy Pasion, Chrstianah Oyenuga, and Kate Gouin, "City of New York Inventory of New York City's Greenhouse Gas Emissions" (New York: Mayor's Office of Sustainability, 2017), http://www.dec.ny.gov/docs/administration_pdf/nycghg.pdf.

[20] United Nations Environmental Programme, *Emissions Gap Report 2018*, November 2018, https://www.unenvironment.org/resources/emissions-gap-report-2018, p. 4.

to paints or wallpapers. The project team and community partners would use the data collected through these sensors, in combination with data science expertise, to design more effective HVAC control systems. The implementation of these project components would take place at Columbia Secondary School in New York City and at least one other site in order to test alternatives. Partnerships with an interdisciplinary Columbia University research team and various public officials would help position the project to be replicated on a broad scale.

In the discussion, multiple participants found the proposed combination of building materials innovative and could imagine them having a large, scalable impact on carbon reduction efforts. Participants questioned, however, whether the pilot envisioned in the project proposal could be accomplished within the CWP-prescribed five-year period. Specifically, two participants questioned whether sufficient market demand existed for the building products identified in the project among contractors renovating building facades and individual building owners, given the lack of current pricing signals for carbon reduction in construction. Another participant suggested the products were limited in that demand, and thus impact, may be limited to a few large urban centers. Additionally, one participant questioned whether this project required the intervention of Columbia World Projects, given that the university might already be equipped to develop and eventually market the proposed components on its own. The project team noted that although similar products are already being produced by project team affiliates in a factory in Mongolia and they are reasonably close to viability, adding different disciplinary expertise might improve their application. For example, participants noted that the university's data science expertise might be leveraged to link the sensors in the third component of the project to data platforms that could further improve their efficiency, while another participant noted that data gleaned from the sensors and the specifications of carbon-free cement could help legislators update building codes, thereby increasing the project's impact.

Carbon-Free Buildings in New York: The second project proposed testing approaches to making the transition from gas, oil, and propane in New York's buildings, to buildings powered by carbon-free electricity, while ensuring that the transition is efficient, equitable, and does not place disproportionate burdens on low-income residents. The project would dovetail with the newly enacted New York State Climate Leadership and Community Protection Act (CLCPA) and look to identify several distinct sites in New York State, which would reflect the diverse types of communities and contexts where such a transition could be tested, in order to generate a set of effective practices that could be adapted by other parts of the State to move toward buildings that rely on electric energy. The project would look to identify the different elements critical to making such a transition – including technical capacity, political will, public engagement and sensitization, behavioral science, regulations and standards, and financial incentives – before undertaking such efforts. It would also aim to measure the impact of such transitions, with special attention to the potential health and thermal comfort impact of moving away from fossil fuels and the economic impacts on low-income or marginalized communities as CLCPA requires. Effectively designing and implementing such a pathway would also require integrating four critically important stakeholders in this transition: the State (and in some instances municipal governments); affected communities; the electric and gas utilities; and public and private financing bodies.

In the discussion, participants emphasized the value that Columbia's expertise could bring to the project, combined with the established network of energy advocacy organizations in the tri-state area to address the challenges associated with attempting to replace the use of existing

fuels – particularly natural gas – on a large scale. Two participants emphasized that the state of New Jersey has invested heavily in natural gas over the past two decades, and that widespread public support for gas heat and cooking fuel exists, which may make gaining traction for the project at scale more challenging. Participants suggested that thought should be given to how to convince consumers to switch to electric energy, including the possibility of encouraging a social movement. Multiple participants noted that it might be easier to focus on promoting the use of electric energy in new buildings, rather than attempting to retrofit old buildings. The project leads noted that a natural entry point for retrofitting existing buildings would be when appliances need to be replaced. One participant also noted that the proposed interventions might create capacity issues for existing energy grids and infrastructure if not implemented as a full grid replacement. At the same time, participants noted that because electric grids in Northeast are generally not under stress in the winter (in contrast to the summer, when they face peak demand), utilities could offer lower cost electric power for heating in the winter, generating economic benefits for the companies, while at the same time providing a cheaper, carbon neutral alternative to heating using fossil fuels. Relatedly, another participant remarked that the project team would need to consider energy storage issues and seasonal usage peaks, which could be challenging to manage without an extensive electricity grid capable of storing reserves. However, other participants countered that hybrid systems, in which gas reserves are engaged to supplement scarce electricity resources during peak usage events, could address the problem. The project leads also noted that the project could advance in a way that incrementally replaced existing utility grids without immediately incapacitating entire systems. Finally, it was noted that much of New York's existing building stock has out-of-date electrical wiring and infrastructure that may be incapable of handling the interventions contemplated, which could present a significant obstacle to retrofitting existing buildings.

Residential Decarbonization in New Jersey for Low- and Moderate-Income Households: The third project focused on how to effectively decarbonize older housing stock for low- and moderate-income (LMI) households in urban settings in New Jersey. Low- and moderate-income households present particularly difficult economic challenges to building decarbonization efforts due to the high cost of heating buildings with electricity rather than natural gas, LMI households' lack of access to credit and capital for energy upgrades, the typically aging infrastructure in their homes, and constraints placed on rental units by landlords. In an effort to overcome these challenges, New Jersey would work with a range of experts from Columbia and leading think tanks, such as the Rocky Mountain Institute (RMI), to design and implement a set of pilots that would test a suite of measures for decarbonizing environmental justice communities in both landlord-owned and tenant-owned homes. The project would ideally consist of pilots in two New Jersey cities, such as Trenton and Newark, and be designed so as to identify a practical, effective way to deliver on key commitments in the State's forthcoming Energy Master Plan, which is expected to be released in late 2019, and will set out a pathway for the State to achieve 100 percent clean energy by 2050.

In the discussion, participants expressed support for the project's proposed focus on LMI communities and the project team's identification of potential funding mechanisms, but voiced concerns regarding the structural challenges associated with transitioning buildings inhabited by LMI households and the behavioral challenge presented by a general consumer preference for natural gas. In considering ways to promote consumer demand for shifting to electricity, one participant noted that other utilities had done so by giving consumers multi-thousand-dollar rebates for switching to electric appliances due to cost savings for the utilities. Another

participant noted that the solar thermal industry had been able to increase consumer demand and might provide relevant lessons. Multiple participants agreed that Columbia University's expertise in behavioral economics and marketing could be leveraged to increase demand. The abundance of up-front funding available for this project's intervention was noted as a potential source of rebates and grants. The project team noted that up-front rebates would likely be preferable to pledging future savings on bills, which have historically been less effective in increasing demand for new products. While one participant said that utility companies would stand to benefit when expensive natural gas pipes no longer needed to be maintained (as a result of the transition to electricity), other participants responded that eliminating natural gas– and thus the infrastructure needed to deliver it – was not feasible in the near future, and thus such savings would not be realized anytime soon. One participant further noted that piloting the interventions in an entire community, as envisioned, might be challenging due to capacity issues related to the potentially excessive demands that would be placed on the existing grid, and consequently, Columbia University's expertise in utility grid capacity modeling might be useful.

Decarbonization and Low-Income Housing: The final project would research and implement an integrated package of initiatives to lower CO_2 emissions while reducing the energy burden for low-income households in urban settings in New Jersey. The project, which was proposed by the Public Service Electric and Gas Company (PSE&G), would focus on three lines of effort in these settings: energy efficiency, renewable energy, and electric vehicle (EV) programs. In terms of implementation, as a first step, household surveys would be conducted to assess each household's existing energy use, the financial energy burden placed on the household, any energy-related health conditions present, and the physical structure's suitability for potential project interventions. While conducting surveys, the project team would also collect information from owners of buildings with low-income renters. This would facilitate future partnerships with building owners, who in many cases would likely present a barrier to low-income households' access to energy-efficiency measures. Following the on-site survey phase, research and analysis would facilitate the design and installation of tailored clean energy solutions to reduce CO_2 emissions.

In the discussion, participants highlighted the potential of this project working in partnership with, or even being combined with, the preceding two projects on "Carbon-Free Buildings in New York" and "Decarbonization of the Built Environment," but again voiced concerns about the complex structural challenges associated with low-income housing (i.e. lack of access to credit and capital for energy upgrades, aging infrastructure in their homes, and landlord constraints placed on rental units) and the project's emphasis on electrification despite strong consumer preference for natural gas. The project leads contended that this issue could be overcome through the project's design, which is focused on consumers and increasing low-income households' demand for upgrades, and includes direct community engagement. A participant additionally noted that faculty from Columbia University are currently undertaking tenant-based surveys in New York related to energy utility messaging that could provide the project with valuable information on changing consumer attitudes. One participant asked whether this project's objective was to achieve deep decarbonization or simply to improve energy efficiency. This question stemmed from the project's focus on natural gas-powered appliances, which might lower the cost of energy for low-income households and make them more energy-efficient, but would likely also result in homes emitting more carbon than if they were to use electric appliances and HVAC systems. The discussion briefly shifted to the

structural and regulatory challenges of energy upgrades, with one participant noting that some residents are barred by regulations from installing solar panels on their rooftops.

Discussion around Potentially Combining Building Electrification Projects: The latter part of the working group session focused on whether the group's four proposals might be combined into a project. Initially, the group discussed which aspects of the project proposals would be most helpful to a state-wide agency like the New York State Energy Research and Development Authority (NYSERDA), and in so doing, participants noted that many of the technological advances discussed would be useful, as would developing effective strategies to shift public opinion and drive market demand for carbon-reducing interventions. Participants then discussed which components cut across all of the projects and could be conceived of as the building blocks of a combined project, settling on the following elements: (i) technological advances in building materials, CO_2 capture within buildings, and energy efficiency or hybrid heating operation (through sensors and data science analytics); (ii) increased knowledge of the public health impact of such transitions; (iii) policy and behavioral interventions to effectively shift the preferences of consumers; (iv) a strategy to drive electrification of heating that accommodates utility constraints; and (v) a financing/incentive strategy. Multiple participants agreed that marrying the technical and practical experience of the utility companies to Columbia University's expertise in behavioral sciences and public health analysis was a priority. Participants then discussed the most appropriate scale for an intervention. Multiple participants viewed small and medium-sized residential buildings as the best option, due to the collective intention to target LMI households, but one participant noted that commercial buildings would be easier to target and less likely to have structural issues. While several participants said that a New York State-focused project testing a comprehensive approach to decarbonizing buildings was well-positioned to provide a model for other states, other participants suggested focusing on narrower, less expensive interventions, the learnings from which could be more widely and swiftly adopted by other states, such as how to shift consumer demand around energy efficient measures. The group concluded that regardless of the specific intervention, a combined project should be pursued given that critically important partners who are not often aligned – in particular a large private utility and state regulatory board – were open to tackling this problem together, and could leverage the expertise of Columbia University to impact their substantial customer bases.

2. Breakthrough Technologies in Storage, Materials, and Capture

Energy needs are projected to increase dramatically in the coming years. As they grow, the demand will be too great to rely solely on existing technologies and policies to reach the decarbonization targets set by the international community. For while the share of the global energy supply that is provided by renewable energy sources is steadily increasing, this has not reduced global carbon emissions as many had hoped, due to the fact that global electricity demand continues to rise.[21] Instead, global energy-related carbon emissions are growing as a consequence of higher energy consumption, due largely to a robust global economy, population growth, and weather conditions that in some parts of the world are leading to increased energy demand for heating and cooling. As a result, public, private, and civil society leaders are

[21] According to one estimate, global electricity demand is expected to increase 57 percent by 2050. "Global Electricity Demand to Increase 57% by 2050," Bloomberg New Energy Finance, September 4, 2018, https://about.bnef.com/blog/global-electricity-demand-increase-57-2050/.

beginning to accept that we will need to find innovative ways to capture and store carbon dioxide from the atmosphere to address the challenge of global warming, as demonstrated by the fact that, for the first time in nearly ten years, 2018 saw an increase in plans to develop large-scale carbon capture and storage.[22] The question remains, however, as to whether it will be possible to scale such plans to meet the challenge. According to UNEP, nearly 50 billion metric tons of GHGs are emitted annually, and avoiding a disastrous level of warming would require not only emissions reductions, but also the removal of some 10 billion metric tons of carbon emissions from the atmosphere each year by midcentury.[23] With this challenge in mind, this working group examined three projects where breakthroughs might be possible in carbon capture, storage, and negative emission technologies.

Solid Carbon: A Climate Mitigation Solution Bringing Together Proven Technologies to Extract CO_2 from Air and Industrial Sources for Permanent Removal: The first project, which would be piloted in the Cascadia Basin off the coast of British Columbia, would pilot a system that permanently removes CO_2 from the air through direct air capture (DAC) and sequesters it below the ocean floor as a harmless solid in basalt rock, which is typically present in the ocean floor. While the subsea injection of CO_2 is now an industry-proven technology, this project would be the first demonstration of both offshore DAC and offshore sequestration through mineralization, powered by renewable sources of energy. A successful, cost-effective, and sustainable demonstration could open the door for safe and permanent removal of atmospheric CO_2 at scale around the world. Additionally, building a tailored regulatory structure around a pilot intended to facilitate and incentivize carbon mineralization would be critical to the success of this effort and entirely novel.

Multiple participants emphasized the innovative nature of the technology and processes that would be deployed in the project, with one participant characterizing it as being at the frontier of scientific discovery. Another participant remarked that moving the DAC offshore would represent a breakthrough, because it might require a reengineering of existing DAC technology. Several participants inquired about site selection, including whether certain concentrations of CO_2 would be required. In response, the project lead noted that sites were identified based upon storage capacity and availability of energy sources, adding that the project is agnostic on the source of CO_2 because varying concentrations can be used effectively in offshore DAC. A participant suggested that the pilot might be better if attached to an offshore oil platform or another industry source, particularly if this could bring the price per ton down from the rough estimate of $200 that the current project proposal anticipates. Another participant raised a question about the storage capacity of subsea rock, and the project lead responded that gigatons of carbon – the equivalent of hundreds of years of U.S. carbon emissions – could be stored for hundreds of years. Some participants asked about the possibility of leakage and the potential consequences if only a portion of the injected CO_2 is mineralized, which is a process that can take years. While the project lead acknowledged that neither precise storage capacity of the reservoir nor the rate of mineralization can be calculated in advance of a pilot study, he stated that any unmineralized carbon dioxide would be trapped below a thick layer of sediment and the overlying ocean. Other potential risks cited by participants included

[22] International Energy Agency, "Global Energy and CO2 Status Report 2018," (March 2019), https://www.iea.org/geco/emissions/.

[23] Jeff Johnson, "Capturing carbon: Can it save us?" *Chemical & Engineering News*, February 25, 2019, https://cen.acs.org/environment/greenhouse-gases/Capturing-carbon-save-us/97/i8.

cost, unintended impacts on ocean chemistry, and obtaining the necessary licenses and permits to operate such a pilot.

Production of CO_2-Negative Concrete from Seawater-Derived Raw Materials: The second project discussed would develop a new process for manufacturing concrete powered by renewable energy that could result in carbon negative emissions. Cement – the key active ingredient in concrete – is one of the most mass-produced materials in the world, with U.S. cement consumption projected to reach 112.7 million tons by 2021,[1] and for every ton of cement produced, it is estimated that 600-700 kilograms of CO_2 are emitted.[24] In fact, the production of Portland cement – the industry standard – accounts for approximately 3.5 percent of global energy consumption and 5 percent of human-made CO_2 emissions. In contrast to conventional calcium-based cement manufacturing, which starts with carbon-containing limestone as the key source material, the proposed process would harvest carbon-free magnesium hydroxide from seawater to produce magnesium-based cement. The harvesting process is driven by membraneless electrochemical reactors, and the resulting magnesium-based source materials will be fed into emerging additive manufacturing schemes to form carbon-negative concretes. If successfully scaled, this project has the potential to eliminate a significant proportion of global CO_2 emissions.

In the discussion, participants raised a number of questions related to cost, scalability, the regulatory structure within which this project would sit, and how to make the process more attractive for adoption by cement manufacturing companies. Several participants noted that many companies are working on alternative cements and cautioned that regulatory issues would need to be resolved to make headway in the historically conservative cement industry. One of the project leads clarified that the proposed process would differ from existing alternative approaches by working with magnesium, rather than calcium-based materials. A number of participants underscored the importance of procurement, noting that government entities are among the largest purchasers of cement, so that meeting certain standards and performance requirements will be central to facilitating market entry even if the cost is low. A participant suggested that engaging with the cement industry would be important to better understand their concerns with respect to liability and customer demand, among other concerns. It was also recommended that the leads emphasize material reduction (i.e. using 50 percent less concrete for the same performance) as a key value proposition of the project.

BioEnergy with Carbon Capture and Storage (BECCS): Negative Emission Technology: The final project discussed would develop and test a modular, mass-producible reactor system to generate bioenergy that can directly convert wet and salty biomass (e.g., seaweed, brine algae, food waste) into green hydrogen for use in producing electricity. This form of generating electricity would be safe and easy enough for individual home use. Biomass is a growing source of energy, contributing 5 percent of the U.S. primary energy supply in 2016.[25] However, it has limited availability compared to fossil resources, and in many cases biomass used in energy production leads to indirect CO_2 emissions when, for example, biomass use results in the loss of

[24] Johanna Lehne and Felix Preston, "Making Concrete Change: Innovation in Low-Carbon Cement and Concrete," Chatham House Report (Chatham House: Royal Institute of International Affairs, June 2018), https://www.chathamhouse.org/sites/default/files/publications/research/2018-06-13-making-concrete-change-cement-lehne-preston.pdf.

[25] Total primary energy refers to the net sum of energy production and imports, excluding energy exports and storage changes.

forests that would otherwise serve as carbon sinks that are key to decarbonization efforts. The use of seaweed and other forms of salty biomass for biofuel production, by contrast, would not result in indirect CO_2 emissions. It also has the advantage of being widely available in many parts of the world and can be cultivated using brine or seawater, enabling many countries with limited land and fresh water to produce bioenergy. This project would use ashes from power plants and waste-to-energy plants, as well as slags from steel and aluminum plants, in a new thermal treatment to convert seaweed to hydrogen. In doing so, it would not only provide a new negative emission approach, but also foster new fundamental insights into the mechanisms of unconventional biomass conversion to green hydrogen, allowing for the efficient use of resources and the conversion and reuse of waste materials. Finally, the project would seek to use the carbonates and biochar that are produced by the alkaline thermal treatment on farm lands, with the aim of improving soil quality and crop production; enhancing carbon storage in soil; and absorbing fertilizers and pesticides into the carbonates and biochar that would otherwise seep down into groundwater.

Much of the discussion centered on questions regarding scale and marketability of the project's bioenergy system, and what sort of pilot would be most likely to lead to a major scaling of the technology. One participant suggested building these reactors for industrial facilities located on a coast or for ports that have easy access to salty biomass – both of which consume large volumes of hydrogen and could present a market for zero-carbon sea fuel. When asked about the ideal scale for optimum impact, the project lead said that the reactor could be built relatively quickly with off-the-shelf technology, which could easily be scaled up after analyzing the amount of CO_2 that can be stored in carbonate form. One participant said the small size of the proposed reactor could make it part of a strategy to electrify buildings, while also directly engaging consumers in carbon management. Participants recommended developing a more precise model of the reactor unit and underscored the importance of applying a lifecycle analysis to the project from the outset in order to credibly demonstrate that the process is truly carbon negative.

3. Transportation and Infrastructure

In recent years, the cost of renewable energy has declined considerably, resulting in wind and solar power being less expensive than any fossil fuel option in many parts of the world today. This development has raised expectations regarding the potential for a widespread shift toward carbon-neutral or even carbon-negative energy systems. Meanwhile, technological advancements in energy storage make it increasingly plausible to draw on renewable sources to electrify high-emissions sectors, particularly transportation. Yet, our current infrastructure and regulatory frameworks are not optimally designed to enable, let alone incentivize, the use of renewables and the subsequent reductions in emissions that could be realized from such a shift. To realize these gains, advances will need to be made in the capacity of the grid and its core components to store, transport, and manage renewable energy. These range from mobile batteries that are capable of storing variable supplies of energy for longer periods of time, to systems capable of optimally matching intermittent supply with demand, to the load shifting that will be required of consumers as a greater proportion of their energy is sourced from solar and wind. The Transportation and Infrastructure working group looked at four projects touching on key challenges in modernizing the infrastructure and technology necessary to meet climate change targets and manage an increasingly renewable supply of energy, and then

discussed the possibility of merging several of the proposals, a summary of which follows that of the individual projects.

Improving Energy Storage for Marine Electrification: The first project would design and test new technologies to facilitate marine electrification in harbors, piloting the approach in the New York City Harbor – a site selected due to its geographic proximity to Columbia, the political will reflected in the ambitious climate targets recently established through legislation passed in New York State, and access to considerable expertise regarding the local regulatory environment. The project would consist of three phases: (i) partnering with key stakeholders to identify the best demonstration vessel for electrification, such as a tugboat, based on cost, load requirements, the willingness of operators to participate, and potential impact; (ii) partnering Columbia researchers with private and public stakeholders to acquire a demonstration vessel (or otherwise have access to the use of such a vessel); and (iii) building a battery management and safety testing platform to address at scale the technical challenges, such as safety, performance, and storage capacity, while simultaneously tackling the legal and regulatory impediments to adoption. Because of energy requirements in a typical usage scenario, as well as proximity to charging ports, near-coastal ships and boats are the most likely short-term candidates for electrification to reduce both CO_2 and the indirect greenhouse gas pollutants – sulfur oxides (SO_x) and nitrogen oxides (NO_x) – that cause significant public health challenges.[26] Hybrid technologies may also be an option to reduce emissions, especially for long-range ships. Electrification of coastal marine transportation offers the additional benefit of improving the water and air quality in busy ports, which could also be measured.

In the working group discussion, participants focused on whether the project could have a significant impact at scale, the likelihood of getting to scale, and challenges associated with implementation. The project leads explained that the focus would be on developing and testing one pilot vessel, with the idea that if the technology were proved to be successful and cost-effective, and if key implementation challenges such as regulatory obstacles could be overcome, it would open the door to much broader adoption. Participants agreed that the field of marine electrification was underdeveloped and ripe for advancement, with interest from the private sector and the military in particular, with one participant noting that the U.S. Navy had agreed in the last year to permit – for the first time – the use of lithium ion batteries on its vessels, something that had previously been prohibited due to safety concerns. Issues related to implementation that were raised as matters to be addressed were fire safety and salt corrosion, both of which are standard issues dealt with in marine engineering, as well as how to integrate the new types of batteries into existing operating systems. The final challenge discussed was that of calibrating the batteries to the thermal profiles and inefficient acceleration of certain boats, with participants suggesting that tugboats, which had already been running on electric power in Europe, might offer the easiest entry point. It was noted that the effort could take advantage of the new Field Station opened by the Lamont-Doherty Earth Observatory and related educational initiatives, with one participant suggesting using the demonstration vessel serve as a floating classroom.

[26] Nick Watts, et al. "Health and climate change: policy responses to protect public health," *The Lancet*, 386, no. 10006 (2015):1861–1914, https://doi.org/10.1016/S0140-6736(15)60854-6; Antoine Halff, Lara Younes, and Tim Boersm, "The likely implications of the new IMO standards on the shipping industry," *Energy Policy* 126, (2019):277–286, https://doi.org/10.1016/j.enpol.2018.11.033; Ara Barsamian and Lee E. Curcio, "IFO380 recipes can meet 2020 reduced-sulfer bunker regs" *Oil & Gas Journal* , January 1, 2018, http://refautom.com/NewsDB/IFO380%202020%20sulfur%20spec.pdf.

Decarbonizing the Grid: The Missing Link of Energy Storage: The second project discussed is premised on the idea that energy storage is the key to unlocking the four economic sectors – transportation, electricity production and transmission, buildings, and industry – that are responsible for up to 80-90 percent of global CO_2 emissions, because it would allow these sectors to draw on wind and solar technologies at scale. The project involves designing, building, and deploying a cost-effective, mobile energy storage system that would overcome existing technical, legal, financial, and regulatory impediments to large-scale deployment of renewable energy generation on the electrical grid by drawing on academic expertise in all of these areas. The pilot would, among other things, demonstrate the potential for battery systems to help the grid manage peak loads, displace peaker fossil fuel plants, and improve grid resilience – all while additionally facilitating faster amortization of the mobile energy storage system, because it will be possible to use it with greater frequency. In its first phase, the project would identify the best mobile demonstration platform, considering the size and whether it should be land- or water-based. Working with one or more utility partners, the project team would design a full-scale battery management and testing platform, and in the second phase, Columbia would partner with stakeholders to acquire and deploy the demonstration system to create a network of mobile energy storage systems. In parallel, researchers would identify additional regulatory requirements that must be satisfied to meet safety standards for permitting deployment not only in New York State, but also in other localities. In the third phase, the battery management and testing platform would be built and used for the purpose of addressing the technical, legal, and regulatory impediments to adoption at a large scale. The demonstration will also help inform research needs based on new challenges that arise during implementation.

Participants in the working group raised questions regarding barriers to finding suitable partners and overcoming regulatory and technical obstacles in New York – the project's intended pilot site. One participant noted that fire department restrictions on lithium batteries had been an impediment in the past, while another suggested that it might be useful to draw lessons learned from research done on lithium batteries in the maritime space. Participants also noted the engineering challenges associated with the mobile nature of land-based systems. These questions notwithstanding, overall multiple participants noted how advantageous a fully scalable battery storage system would be compared to a peaker power plant. Additionally, participants discussed the distinct value that such a system might provide both in countries with poorly developed grids as well as in countries like the United States with high-quality grid capacity but a limited ability to integrate renewables.

Integrating Renewable Energy into the New York Grid: The third project examined would develop and test a unified framework for analyzing the right combination of three approaches for managing the intermittency challenges that will arise with the shift toward a greater reliance on renewables. The first approach is demand management – essentially paying power users to reduce demand when there is a shortfall in supply. The second is energy storage, which historically has taken the form of pumped hydroelectricity, but is increasingly implemented through the installation of large batteries that can store power from times of surplus for use in times of shortage. And a third is investment in a geographically diverse set of wind farms to ensure that the covariances between some of these farms are negative (in other words, selecting a range of locations to ensure a steady wind supply). While implementing any one of these

approaches alone will be insufficient to address the challenges presented by intermittency, the framework would aim to determine the combination of these approaches that would enable a maximally reliable supply. The framework would be tested in New York State, which has an ambitious plan to increase the role of intermittent wind energy in its grid, and where the utility, ConEdison, has a well-developed program for demand management. The idea is that an accurate and cost-effective way to model the tradeoffs between these three approaches will provide a pathway to more rapidly overcome the challenges of managing intermittent energy supplies far beyond New York State.

In response, one participant noted that spatially diverse modeling is critical because, for example, New York City's grid alone is made up of 14 separate zones. The participant also advised that data from the project could help inform legislative initiatives to promote decarbonization. Another participant suggested that Columbia's expertise might be especially useful in helping to design such legislative initiatives, in addition to identifying institutional obstacles. Participants underscored the importance of differentiating between generation, transmission, and distribution systems, and taking into account the implications of a shift to renewables for all three. One participant pointed out, for example, that the majority of ConEd's costs are not in power generation, but rather in transmission and distribution, which will remain high even as there is a greater reliance on renewables. The concluding portion of the discussion saw multiple participants brainstorming potential challenges, including how to simulate battery power and distribution and how to account for operation and maintenance costs that will grow with time.

Electrifying New York City's Bus Fleet: The final project discussed would work with the City of New York to meet its goal of electrifying its bus fleet by 2040, drawing upon the lessons learned from cities such as Shenzen and London. Researchers and scholars from Columbia University would assist the City of New York in developing (i) a regulatory framework; (ii) a plan for managing electricity loads and rates; (iii) a proposal for deploying and operating electric buses; and (iv) a blueprint for designing the supporting infrastructure. Key considerations in the evaluation and design of these plans would include cost-effectiveness, technological availability, political viability, and operational integration. The project team, led by EVery City, would work to bridge partners and lead a group of scholars and researchers to address a series of research questions that would assist the transition. Chief components of the research would include route optimization for phases of electric bus implementation, siting of on-route opportunity charging, solutions for consumer responsiveness to time-varying rates, and analysis for price-setting of a Low Emissions Zone (LEZ) charge. This project would not only assist New York City in transitioning its bus fleet to electricity but also promote best practice models for other cities around the country.

During the discussion, participants explored ways in which energy from other transportation systems could be harnessed for powering buses. The project team suggested that energy created by braking subway cars could be used for bus electrification, citing a project in Philadelphia testing this process. A participant noted that energy from subway car braking could be distributed widely, not just to buses; indeed, the transfer to buses might not be the most efficient use of such energy, another participant noted. It was noted that while some of the lessons from bus electrification in China might be relevant to New York, other factors may make the model less relevant, such as the distinct political and regulatory environments and,

one participant added, different perspectives regarding the safety standards that must be met before a new technology can be implemented.

Discussion around Potentially Combining Transportation and Infrastructure Projects: The working group concluded its discussion by considering whether combining any of the proposals discussed would be advantageous. One participant proposed grouping the projects in two categories: transportation (marine and bus electrification) and infrastructure (intermittency modeling and mobile batteries). Another participant suggested that combining the marine and bus electrification projects could present the opportunity for constructing a dual-use facility for developing and testing storage technology. A discussion followed as to whether there was still the need for innovation with respect to renewable bus batteries or whether sufficient progress has been made, as well as whether advances in renewable marine and bus technology would be mutually beneficial. Multiple participants argued against combining the marine and bus electrification projects, with one participant arguing, for example, that the bus project presented more of an implementation, policy, and marketing challenge, whereas the marine project also presented significant technological and regulatory challenges. Participants then discussed cross-project considerations, including how to measure the impact of each project on pollution. For example, a participant advised groups to measure marine and bus electrification would improve air and water quality, and the corollary impact of those improvements on public health. The group also considered why the projects were more viable as Columbia World Projects than as investments to be taken up by the private sector.

4. Tracking and Measuring Emissions to Change Practice

Private sector actors are increasingly making public commitments and launching efforts to address climate change, driven by a combination of the advent of new policies and regulations, a sense of duty in the face of government inaction, and the conclusion that it is good for business. Since the Trump administration announced its intention to leave the Paris Agreement, for example, more than 2,200 U.S. companies have signed a pledge indicating they are committed to reducing their emissions consistent with the U.S. commitment under the accord.[27] Similarly, more than 600 companies have adopted "science-based targets" that set ambitious GHG emission reduction targets in line with the aims of the Paris Agreement,[28] and an estimated 45 Fortune 100 companies have made climate commitments.[29] These commitments represent an important means of achieving decarbonization, whether businesses perceive such measures as bolstering their bottom line; representing a new form of corporate responsibility; responding to increasing consumer demand for sustainability; or some

[27] The United States submission under the Paris Climate Accord, referred to as an Intended Nationally Determined Contribution, pledged to reduce emissions by 26-28 percent below its 2005 level by 2025, and to make best efforts to reduce emissions by 28 percent. "Fact Sheet: U.S. Reports its 2025 Emissions Target to the UNFCCC," March 31, 2015, https://obamawhitehouse.archives.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc; Who's In," We Are Still In, accessed September 11, 2019, https://www.wearestillin.com/signatories.

[28] "Companies Taking Action," Science Based Targets, accessed September 11, 2019, https://sciencebasedtargets.org/.

[29] "Customer Renewables Initiative: Corporate Climate Tracker," David Gardiner and Associates, accessed September 11, 2019, https://www.dgardiner.com/corporate-climate-tracker/.

combination of these and other factors. These commitments, however, have not always translated into concrete action, and even when they have led to action, because the emissions have not been adequately tracked and measured, it is not clear to what extent such commitments have led to reductions in GHG emissions. Transparently tracking and measuring private sector pledges could not only increase collective understanding of the actual impact of such pledges and help companies identify new ways to effectively reduce emissions, but could also potentially create additional public pressure on companies to follow through on such pledges. This working group considered two projects that would employ innovative and accurate ways to track and measure emissions, and apply what is learned to reduce emissions across companies' supply chains.

Reducing Methane Emissions from the Oil and Gas Industry: The first project proposal involves academics from a variety of fields partnering with Columbia's Center on Global Energy Policy (CGEP), the Environmental Defense Fund (EDF), and progressive oil and gas companies willing to set aggressive targets for reducing methane emissions. In addition to raising awareness among key stakeholders of methane's significant impact on global warming and improving the public's understanding of where and why methane emissions are occurring, the project would aim to use new satellite technology launched by EDF, along with other available data, to establish credible metrics for tracking and measuring methane emissions by the oil and gas industry. This, in turn, would make it possible not only to credibly determine whether companies that have pledged to reduce emissions are in fact doing so, but also to collaborate with public and private sector leaders in the field on the design of meaningful methane reduction strategies. Methane is one of the chief contributors of anthropogenic global warming. According to the IPCC, methane emissions from human activities are driving more than a quarter of the warming on our planet today, and the global oil and gas industry is responsible for roughly one-third of these emissions. Nevertheless, the precise magnitude and sources of oil and gas methane emissions are poorly understood, hampering the ability to reduce emissions. The project would build on Columbia's expertise in earth and environmental sciences, engineering, data science, statistics, economics, and the law, as well as and its network of Global Centers. Through sustained engagement and increasing awareness, the project aims to expand the number of industry leaders willing to set aggressive targets and adopt practices for reducing the methane emissions, particularly among national oil companies, and to provide the transparency needed to develop stronger methane regulations.

Participants in the working group raised a number of key questions regarding the project, including: (i) why EDF was unable to pursue such efforts on its own and what unique value Columbia would add to the project; (ii) whether the project should focus solely on the oil and gas industry, as opposed to other sources of methane emissions; (iii) whether efforts to reduce methane emissions could have the effect of promoting natural gas use and consequently stall the transition to solely renewable energy sources; and (iv) whether the project should additionally focus on attempting to design and promote a regulatory structure that would incentivize the reduction of methane emissions. Working through these questions, participants discussed the exceptional global platform that Columbia University, and in particular CGEP and the Global Centers, provide as a convener with the capacity to draw stakeholders from government, industry, and nongovernmental organizations whose participation would be necessary to expand EDF's work in this area, in addition to the academic expertise that would be available across a range of topics critical to analyzing the impact of methane emissions, understanding the patterns of such emissions, developing useful metrics for tracking and

measuring emissions, and designing strategies through which industry could plausibly reduce such emissions. Additionally, given the discussion surrounding the importance of a regulatory structure for incentivizing such emissions, the view was that Columbia University's expertise in designing an effective regulatory framework would be another key contribution. This part of the project might be further developed, it was noted, including by adding as a partner in the project a jurisdiction interested in adopting a regulatory framework for methane emissions that could be informed by the success of methane reduction strategies tested under the auspices of the project.

In response to concerns about stalling a transition to renewables, the point was made that we should not ignore existing methane emissions that are having an enormous impact on global warming simply because we are concerned that this might slow down a transition to renewables. Moreover, it was noted that renewables do not substitute for oil and gas in many applications at present, from heating to industry to parts of transportation. Additionally, when considering the scope of the project and whether the focus should be solely on methane emissions that arise from the oil and gas industry, the point was made that progress on oil and gas industry emissions could plausibly be made in a relatively short period of time and requires a different set of solutions than reducing emissions in agriculture, for example.

Decarbonization from Within: Empowering Companies to Reduce the Carbon Embedded in Everyday Products: The second project discussed by the working group would refine and test a data science-based approach to determining the life cycle GHG emissions of any set of products in any company, potentially analyzing tens of thousands of products at one time. Most anthropogenic greenhouse gas emissions are embedded in the life cycle of products, from the emissions that originate outside a company's direct operations, namely in the "upstream" supply chain of raw materials used in manufacturing and the "downstream" processes such as consumer use and disposal. While many companies apply life cycle analysis (LCA) to individual products, up to now, LCA has mostly been a manual undertaking that is prohibitively expensive to carry out at scale, sometimes costing upwards of $10,000 per product. Thus, rather than conducting LCA across a company's portfolio of products, the focus has instead been on generating an annual GHG emissions report for a company as a whole, which is both a less granular way to estimate the carbon footprint of companies, and is less likely to promote positive shifts in corporate and consumer behavior to minimize emissions. This project would partner Columbia University experts with the Colgate Palmolive Company and perhaps an additional company to apply "fast product carbon footprinting" technology to a suite of consumer products to accurately measure GHG emissions, use the results to inform corporate sustainability decision-making, and quantify Colgate's GHG reduction achieved as a result. This project could demonstrate the effectiveness and scalability of this technology and its potential for reducing GHG emissions, as well as promote the application of LCA to products by other companies through consumer education and knowledge hubs.

Several participants asked for greater clarity on how this technology would differ from conventional methods of LCA. In response, one of the project leads noted that, in addition to lowering the cost, existing methods often have missing data and incomplete information about emissions over the full value chain of a product. This is an area in which artificial intelligence and machine learning tools can help by, for example, using out-of-sample predictions of missing values with machine learning algorithms to close data gaps. Several participants were supportive of the project's scalability but inquired about the specific mechanism by which the

approach would scale to thousands of products. In response, the point was made that the focus could be on multinational companies that would have a significant impact across multiple sectors. This led to a broader discussion about whether supply- or demand-side forces would be more likely to compel a company to adjust its practices in light of new information about GHG emissions. One project lead reported that some consumers are increasingly demanding such details about the products they purchase, and companies that adopt this new technology might obtain a first-mover advantage, while significantly expanding the number of products that can be analyzed. However, another participant responded that the scale of consumer-driven demand for lower emissions in products was limited and most consumers had not yet demonstrated a willingness to pay a cost premium for products with a smaller carbon footprint. In citing a potential risk, one participant noted that a company's decision to implement changes based on what it learns through "fast product carbon footprinting" may depend on consumers' willingness to pay more for products that yield lower emissions. Some participants suggested that, given the potential commercial value of the technology, the project could be an opportunity to test innovative business models such as a social enterprise – rather than defaulting to a nonprofit entity – and should consider sustainability from the outset.

5. Policy Innovation

Existing market forces and public pressure to address the impact of climate change, while critically important, are not sufficient to produce meaningful progress. Consequently, novel and effective government action must be pursued to facilitate, if not incentivize, the reduction of GHG emissions. Unfortunately, however, thus far the policies of the world's biggest carbon emitters have been at best inadequate and at worst counterproductive in attempting to establish an environment in which emission targets are likely to be met. To give just one example, subsidies for fossil fuels remain in place in at least 112 countries and actually increased by 11 percent in 2017.[30] Such subsidies are roughly double the amount governments have allocated to supporting renewable energy. In the face of insufficient national action on these issues, a number of subnational entities such as states, counties, and cities have put in place policies – some mandatory, others voluntary – to foster innovation, reward reductions and capture, and penalize emissions. This group examined two projects that would help to identify and test the optimal policies for promoting decarbonization efforts, each to be led and implemented by a national government: one focused on a carbon pricing system, and the other on Power-to-X (PtX) technologies.

Carbon Pricing and Clean Energy Transition in Chile: The first project discussed would develop a model to identify and design the most economical climate policies, based on the cost of measures to reduce GHG emissions relative to the potential magnitude of such reductions, and help identify the optimal timing and sequencing to implement these measures, as Chile strives to achieve carbon neutrality by 2050. While progress must be made across all sectors to reach Chile's targets, the government must make strategic choices around how to invest its resources in order to maximize their impact on decarbonization targets and optimize their benefits for the country and its people. If designed correctly, the model would allow Chile's decarbonization efforts to focus on the sectors with the most cost-effective mitigation technologies, while identifying incentives to promote greater efficiency and informing the

[30] David Roberts, "The global transition to clean energy, explained in 12 charts," *Vox*, last updated June 26, 2019, https://www.vox.com/energy-and-environment/2019/6/18/18681591/renewable-energy-china-solar-pv-jobs.

legislative strategies required to implement the selected policies. Furthermore, the new model would integrate models of energy demand with economic and human behavior models, in order to better predict the impact of these public policies over time, enabling a technical-economic evaluation of prospective and current mitigation measures by considering the cost of investment, operation, and maintenance.

In reviewing the project, participants suggested that it would be important to: (i) identify the relevant academic research that could contribute to developing the kind of complex models around cost and impact of climate policies in Chile that would be necessary to develop the comprehensive model envisioned in the context of the project; (ii) specify measurable actions from the model that could be implemented and evaluated; (iii) develop a market and trading platform for the complex modeling envisioned; (iv) incorporate scoring functions into the model that accurately weigh the cost versus the impact of selecting certain policies; and (5) apply a more equitable understanding of economic growth to the modeling process, making it possible to balance growth and development with the environmental cost of certain policy choices. On the issue of equity, it was suggested that Chile could become the standard bearer for incorporating social dimensions of climate policy. It was also suggested that the project should have the ambition to generate a model for the region, rather than be one that is country-specific, given that Chile alone could source 20 percent of the renewable power needs of South America.

Power-to-X: The Missing Link in Decarbonization?: The second project would focus on how to develop and implement a policy framework that applies Power-to-X (PtX) technologies[31] to Denmark's wind energy resource. Denmark has set the ambitious target of reducing greenhouse gas emissions by 70 percent by 2030, and meeting this target will require unprecedented action across sectors including deploying Denmark's abundant renewable energy in forms other than electric power. PtX has the potential to offer pathways by which surplus renewable power could be used to produce green chemicals and fuels for use in other parts of the economy. More generally, PtX may make it easier to transition from fossil fuels to a sustainable world by increasing the share of e-fuels, which can be synthesized into the fuel mix using negative-carbon emission techniques, and therefore would not require immediate changes in today's fuel infrastructure and end-user applications. The project would partner Columbia University researchers with the Danish government to develop solutions that address key barriers to advancements in PtX, including the technical, regulatory, geographic, and market dimensions of the issue.

During the discussion, there was consensus among participants that PtX represents a potentially transformative strategy of decarbonization if renewable energy can be harnessed to drive the production of new materials using existing carbon. One participant noted that electrolysis needed for PtX requires gigawatt scale renewable facilities that do not currently exist in Denmark and would require a substantial capital investment. The participant

[31] Power-to-X or PtX does not have a universally accepted definition but generally refers to pathways that use surplus power, typically electric power during periods where fluctuating renewable energy generation exceeds the load with the idea of storing the power produced for use at a later date. This might be achieved by, for example, converting electrical energy into a liquid or gaseous chemical energy source through electrolysis and further synthesis processes, which would then be used to fuel other activities months later, though note that grid-dedicated batter storage is not normally considered to be a power-to-x concept. PtX is also understood by some to refer to conversion technologies that facilitates sector coupling.

highlighted the importance of identifying both the right chemical processes and the market for new products of PtX, while also pointing to the need to diversify outputs that do not further contribute to GHG emissions. One participant noted that if CO_2 is needed to generate new products, such as methane or e-fuels, through PtX, Denmark must decide whether to focus on direct air capture, which would require processing massive amounts of air and huge capital investments, or connecting to an industrial point source. A participant suggested that creating new fuels could also pose a challenge for recycling byproducts from the biological processes used in PtX. However, another participant posited that the healthcare sector could benefit from PtX byproducts, as many materials used in the sector are petroleum byproducts. In response to a question about barriers to PtX, the project lead commented that some opposition could come from sectors that use fossil fuels, although there will still be a need for petroleum-based products in the near term. Bringing in major Danish private sector partners could help ameliorate political opposition to implementing PtX. Several participants pointed to the need for greater specificity regarding the project's timeline, measurable impact, and the value-add of Columbia research. When asked about the viability of the project within the five-year timeframe prescribed by CWP, the project lead remarked that the next couple of years will be critical to developing the model of PtX, and Columbia's expertise could assist in identifying financial and policy incentives, developing technological options, and convening all necessary stakeholders.

III. Conclusions and Project Selection

When participants reconvened in the Forum's closing plenary session, the five moderators reported out on the ideas discussed in their respective working groups, the decarbonization challenges each sought to address, and the feedback each project had received from the group's experts. Next, each participant was asked to identify the one or two projects that she or he thought most merited further development by CWP for potential implementation. There was broad support for three projects, which, as a result, we intend to bring to the CWP Advisory Committee for consideration. There was also notable support for three additional projects that will undergo further review, the results of which will determine whether they are also presented to the CWP Advisory Committee.

The first project that received considerable support was "Solid Carbon: A Climate Mitigation Solution Bringing Together Proven Technologies to Extract CO_2 from Air and Industrial Sources for Permanent Removal," which would test and demonstrate a novel process for carbon capture and storage that combines offshore direct air capture with sequestration through mineralization below subsea basalt rock, to be piloted in the Cascadia Basin off the coast of British Columbia. The process would be powered by renewable sources of energy, and a successful, cost-effective, and sustainable demonstration could open the door for safe and permanent removal of atmospheric CO_2 at scale.

The second project was "BioEnergy with Carbon Capture and Storage (BECCS): Negative Emission Technology," which would develop and test a modular, mass-producible reactor system that converts wet and salty biomass (e.g., seaweed, brine algae, food wastes) into green hydrogen for use in producing electricity. This form of electricity would draw upon a thermal process using seaweed as an alternative biomass for fuel production (given its wide availability globally) and would be safe and easy enough for home use. After testing a prototype in a controlled environment, these systems could be quickly scaled-up, facilitating the rapid

deployment of this technology. The project would aim not only to develop a new negative emission approach towards decarbonizing the energy sector, but also foster new insights into converting unconventional biomass to green hydrogen and using the waste materials (carbonates and biochar) on farm lands to improve soil quality and protect groundwater.

The third project was "Reducing Methane Emissions from the Oil and Gas Industry." This project would partner Columbia researchers with the Environmental Defense Fund (EDF), leveraging new data from EDF's MethaneSAT satellite to establish credible metrics for tracking and measuring methane emissions in the oil and gas industry. This new capacity for external verification will raise awareness of the serious problem of methane leakage and will enable the design of effective methane reduction strategies among key stakeholders. The project would aim to tackle the problem in partnership with the global oil and gas industry, which is responsible for roughly one-third of these emissions, and prioritize both expanding awareness of the problem and building support for actions to reduce emissions among national oil companies along with the international companies already engaged on the issue. Building on Columbia's s in Earth Science, its expertise in policy design and its track record of developing solutions with policymakers and industry through the Center on Global Energy Policy (CGEP), and its network of Global Centers, the project would convene experts and engage policymakers, progressive oil and gas companies, and leading NGOs to expand the number of industry leaders – especially national oil companies – willing to adopt practices and set targets for reducing methane emissions.

These three projects will be presented to the CWP Advisory Committee in November, soliciting members' views on whether CWP should develop the proposals further.

Experts cited a number of reasons for supporting these projects. During both the opening and closing plenary sessions, participants stressed the importance of selecting projects that would bring Columbia's role as a university and its comparative expertise to bear on the challenge by adding unique value to the project. Participants noted that both the "Solid Carbon" and "Bioenergy" projects would draw upon Columbia's leading expertise in Earth sciences and engineering. Mineralization, in particular, is only conducted by a small number of institutions, reflecting a unique opportunity and strength of the "Solid Carbon" proposal. One participant also observed that Columbia has a vital role to play in incentivizing offshore direct air capture and sequestration given its limited appeal to the private sector at the current time. Additionally, several participants highlighted the essential role that carbon capture and sequestration will play as part of a broader decarbonization strategy. Both "Solid Carbon" and "Bioenergy," they said, incorporate sequestration, which is a crucial step to removing carbon in the short-term while continuing to explore and develop additional decarbonization technologies.

Overall, the three projects were praised as demonstrating innovation and the capacity to have a concrete impact on the specific problems they aim to address. The "Methane" project in particular was cited as tackling a dimension of the climate crisis for which there has been much talk but little action. Participants noted that, if successful, it could have an outsized impact on reducing greenhouse gas emissions in the oil and gas industry in a relatively short period of time.

Three additional projects received significant support for further development by CWP, though not as much as the prior three projects. The first, Decarbonizing from Within: Empowering Companies to Reduce the Carbon Embedded in Everyday Products would partner Columbia researchers with the Colgate Palmolive Company to develop and apply a data science-based, scalable process to determine the life cycle GHG emissions of the full portfolio of a company's products (tens of thousands of products in a company like Colgate Palmolive) in a way that is cost-effective and efficient, and then using the results to inform the company's decision-making and sustainability operations. The second, Improving Energy Storage for Marine Electrification, would design and test a new approach to electrifying marine transportation vessels in New York City Harbor, informing research, design, and development of the next-generation systems that are safe and cost-effective, with the aim of catalyzing broader electrification in the maritime sector. For this project, a key concern is whether there is a viable practitioner partner that would work with the Columbia faculty in the design and implementation of the marine vessel. The third project would bring together a number of proposals from the working group on Decarbonization of Buildings that aim to reduce the carbon footprint of the built environment through electrification, with a particular focus on facilitating clean energy transitions among low- and moderate-income households in New York and New Jersey. A major question with respect to this project is whether there is a core group of Columbia faculty who would be interested and able to bring the research and scholarship expertise to bear on the challenges posed by this project, in partnership with the public and private practitioners who proposed working on this issue. CWP staff will focus on these and other key questions related to CWP's criteria in the coming weeks, after which a decision will be made about whether they will be presented to the CWP Advisory Committee.

IV. Next Steps: Project Development, Assessment, and Implementation

In November 2019, the most promising project ideas selected by the Forum participants will be presented to the CWP Advisory Committee, whose role is to advise on whether project ideas coming out of the Forum meet CWP's criteria and merit further development as potential CWP projects.

Projects that are determined to merit further development will receive an initial tranche of funding to undergo a rigorous project design phase of approximately six months, during which the project leads will work with CWP staff to define major deliverables, a precise timeline for implementation, a funding plan, a set of performance indicators for monitoring and evaluation, and the key implementing partners – all of which will be synthesized in a project design report. CWP staff will then prepare an evaluation of this plan, which will be combined with the project design plan and shared with Columbia President Lee C. Bollinger and the CWP President's Council for final consideration.

V. Acknowledgements

A number of people helped conceive of, organize, and shape the CWP Forum on Decarbonization to whom we are profoundly grateful.

First, we thank the many individuals who gave generously of their time in advance of the Forum, informing our understanding of the challenge, helping develop ideas for specific projects, and suggesting potential partners for implementation. They include (unless otherwise noted, the institution with which individuals are affiliated is Columbia University): Kåre Aas, Ambassador of Norway to the United States; Jan Andersen, Business Development Director, Americas, DNV-GL; William Boyd, Professor of Law, UCLA School of Law; Deborah Coen, Professor, Department of History, Yale; Jane Cohen, Policy Advisor, Office of Governor Phil Murphy; Patricia Culligan, Robert A.W. and Christine S. Carleton Professor of Civil Engineering; Fan Dai, Founding Director, California-China Climate Institute, UC Berkeley; Jonathan Elkind, Senior Research Scholar, the Center on Global Energy Policy; Anna Escuer, Lead for Carbon Sustainability Strategy & Operations, Google; Paula Estévez, Head of International Department, Ministry of Energy, Chile; Phillipe Fonta, Founder and CEO, SCRUM-Consult; Vasilis Fthenakis, Senior Research Scientist, Founding Director of the Center for Life Cycle Analysis; Antoine Halff, Senior Research Scholar, Center on Global Energy Policy; Victoria Hamilton, Executive Director, Research Initiatives, Office of the Executive Vice President for Research; Marsden Hannah, Senior Lead, Global Energy Policy and Market Development, Google; Melanie Hart, Senior Fellow and Director of China Policy, Center for American Progress; John Holmes, Director, National Academies of Sciences; Radley Horton, Lamont Associate Research Professor; Radley Horton, Lamont Associate Research Professor, Earth Institute; Ralph Izzo, Chairman, President, and CEO, PSE&G; Rohit Khanna, Program Manager, ESMAP, World Bank; Emmanuel Kattan, Director of the Alliance Program; Nathaniel Keohane, Senior Vice President, Environmental Defense Fund; Jacqueline Klopp, Co-Director, Center for Sustainable Urban Development; Peter Levi, Energy Analyst, International Energy Agency; John J. MacWilliams, Fellow, the Center on Global Energy Policy; Trieu Mai, National Renewable Energy Laboratory; Genevieve Maricle, Global Knowledge and Innovation Lead, Climate and Energy Practice, World Wildlife Fund; Reinhold Martin, Professor of Architecture; Ben Orlove, Professor of International and Public Affairs; Janos Pasztor, Senior Fellow and Executive Director, Carnegie Climate Governance Initiative; Michelle Patron, Director of Sustainability Policy, Microsoft; Justin Pearlman, Chief of Staff to the Provost; Karen Poniachik, Director, Columbia Global Center Santiago; Dylan Possamai, Assistant Professor of Industrial Engineering and Operations Research; Brad Plumer, reporter, The *New York Times*; Graham Pugh, Clean Energy Solutions Center; Cynthia Scharf, Senior Strategy Director, Carnegie Climate Governance Initiative; Jasmin Sharzad, Officer, Ministry of Climate, Energy and Utilities, Denmark; Sumant Sinha, Chairman and Managing Director, ReNew Power; KR Sridhar, Founder and CEO, Bloom Energy; Jennifer States, Senior Consultant and Business Development Manager, DNV-GL; Hannah Thonet, Bureau Chief of Policy, Office of Clean Energy, New Jersey Board of Public Utilities; David Turk, Head of Strategic Initiatives, International Energy Agency; Bruce Usher, Co-Director of the Tamer Center for Social Enterprise and Professor of Professional Practice; David Victor, Co-Chair, Cross-Brookings Initiative on Energy and Climate; Jennifer Wenzel, Associate Professor of English and Comparative Literature; Romany Webb, Senior Fellow and Associate Research Scholar, Sabin Center for Climate Change Law; Jim Williams, Associate Professor, University of San Francisco; and Mike Winka, Senior Policy Advisor, Office of Policy and Planning, New Jersey Board of Public Utilities.

Second, we are deeply indebted to the moderators of the Forum's working groups, who went above and beyond to facilitate discussions of proposed projects and improve our work in all

respects: Richard Kauffman (Decarbonization of Buildings); John Podesta (Breakthrough Technologies in Storage, Materials, and Capture, session 1), Julio Friedmann (Breakthrough Technologies in Storage, Materials, and Capture, session 2), Andrew Revkin (Transportation and Infrastructure), Brian Deese (Tracking and Measuring Emissions to Change Practice), and Noah Kaufman (Policy Innovation).

Third, we thank the experts who enriched the conception of specific projects and their discussion in the Forum's working groups: Kirsten Brosbol, Obama Foundation Scholar; Xiaofan Jiang, Assistant Professor, Electrical Engineering and Computer Engineering; Shiho Kawashima, Associate Professor, Civil Engineering and Engineering Mechanics; Matthew Koenig, Principal Consultant, Business Development, DNV-GL; Brian Mateo, Assistant Dean for Civic Engagement, Bard College; Jeff Peterson, Senior Advisor for Entrepreneurship, NYSERDA; James Wilcox, Project Manager, Energy and Environmental Analysis, NYSERDA.

Fourth, we extend our appreciation to the Columbia students and fellows who supported the working groups at the Forum: Harshil Bansal, Anna Dorfi, Ala Douba, Zach Jones, and Rob Mohr; Tyler Haupert, for his considerable help in research and editing; Kristin Benzinger, Joanna Dozier, Britt Hefelfinger, Molly Hellauer, Katyanna Johnson, and Christina Shelby from Office of the President; Pat Lilly, Kim Milian, and Mary McGee from the Forum; to Jack Lynch and the team at the Lenfest Center for the Arts; CWP staff Tom Asher, Ann Borns, Malo Hutson, Sue Radmer, Hillary Schrenell, Christopher Shea, Samantha Slater, and Lily Wendle; and special thanks to Cassandra Ziegler. Additionally, this Forum would not have happened without Ari Shaw who, in partnership with Nik Steinberg, the CWP Forum Director, spent countless days and hours working with participants and experts, drafting and editing papers, and effectively curating the Forum process. We are so grateful for their tireless efforts. Finally, our greatest thanks go to the Forum participants, many of whom went above and beyond the call in helping us to design the work of the Forum and who are listed in the annex that follows.

VI. Annex: Biographies of Forum Participants

Lee C. Bollinger
President, Columbia University
Lee C. Bollinger became Columbia University's nineteenth president in 2002. Under his leadership, Columbia stands again at the very top rank of great research universities, distinguished by comprehensive academic excellence, historic institutional development, an innovative and sustainable approach to global engagement, and unprecedented levels of alumni involvement and financial stability. President Bollinger is Columbia's first Seth Low Professor of the University, a member of the Columbia Law School faculty, and one of the country's foremost First Amendment scholars. As president of the University of Michigan, Bollinger led the school's historic litigation in *Grutter v. Bollinger* and *Gratz v. Bollinger*. These Supreme Court decisions that upheld and clarified the importance of diversity as a compelling justification for affirmative action in higher education were reaffirmed in the Court's 2016 ruling in *Fisher v. University of Texas*. As Columbia's president, Bollinger conceived and led the University's most ambitious expansion in over a century with the creation of the Manhattanville campus in West Harlem. An historic community benefits agreement emerging from the city and state review process for the new campus provides Columbia's local neighborhoods with decades of investment in the community's health, education, and economic growth.

Morten Baek
Permanent Secretary of State, Danish Ministry of Climate, Energy and Utilities
Morten Bæk joined the Ministry of Climate, Energy and Building at its creation in November 2007, serving as head of the Minister's Private Office, the Department of National Energy Policy and the Department of Administrative Affairs. From 2011 until his appointment as Director General, Bæk headed the Ministry's International and Budgetary Affairs as Deputy Permanent Secretary. A former diplomat, Bæk was stationed in Washington D.C. 2004-2007, and worked with Danish Security Policy, European Affairs and Development Assistance Policy in the Ministry of Foreign Affairs. He started his career in consulting, working for Accenture Ltd. and Danish Rambøll Management. He holds a M.A. in Political Science from Copenhagen University and a B.A. in Political Science from Aarhus University.

Scott Banta
Vice Chair and Professor of Chemical Engineering, Department of Chemical Engineering, Columbia University
Scott Banta is a Professor and the Vice Chair of Chemical Engineering at Columbia University. His research focuses on biochemical engineering and synthetic biology for applications in areas including biocatalysis, bioelectrocatalysis, biomaterials, biosensing, biomining, carbon capture, and bioenergy. His group is actively developing new biotechnology platforms for energy harvesting and conversion, including power-to-fuel technologies. He serves as an Associate editor for the

Biochemical Engineering Journal and is a member of the Consulting Editorial Board for the American Institute of Chemical Engineers (AIChE) Journal. He is the Long Range Program Coordinator for the Biochemical Technologies (BIOT) Division of the American Chemical Society (ACS) and he is a Fellow of the American Institute for Medical and Biological Engineering (AIMBE).

Jason Bordoff
Professor of Professional Practice in International and Public Affairs, Columbia University; Founding Director, Center on Global Energy Policy
Jason Bordoff joined the Columbia faculty after serving until January 2013 as Special Assistant to the President and Senior Director for Energy and Climate Change on the Staff of the National Security Council and, prior to that, holding senior policy positions on the White House's National Economic Council and Council on Environmental Quality. One of the world's top energy policy experts, he joined the Administration in April 2009. At Columbia's School of International and Public Affairs, Bordoff is a professor of professional practice and serves as founding Director of SIPA's Center on Global Energy Policy. Prior to joining the White House, Bordoff was the Policy Director of the Hamilton Project at the Brookings Institution. He is a member of the Council on Foreign Relations and the National Petroleum Council, a consultant to the National Intelligence Council, and serves on the boards of Winrock International, the New York Energy Forum and the Association of Marshall Scholars. Bordoff graduated with honors from Harvard Law School, holds an MLitt degree from Oxford University where he studied as a Marshall Scholar, and BA magna cum laude and Phi Beta Kappa from Brown University.

Mark Brownstein
Senior Vice President, Energy, Environmental Defense Fund
Mark Brownstein is Senior Vice President of Energy at Environmental Defense Fund, and a member of EDF's executive team. The goal of the EDF Energy Program is to bend the curve on greenhouse gas emissions from oil and gas production and use by 2030, while meeting the world's energy needs cleanly and equitably. Brownstein is on the advisory board of the University of Pennsylvania's Kleinman Center for Energy Policy and a former member of the National Petroleum Council and the Electric Power Research Institute's public advisory board. He is an adjunct professor of law at New York University Law School where he co-teaches a seminar on public policy and energy project finance. He has also taught energy policy at Columbia University's School of International and Public Affairs (SIPA). Brownstein's career includes time as an attorney in private environmental practice, an air quality regulator with the New Jersey Department of Environmental Protection, and an aide to a member of the U.S. House of Representatives. He holds a J.D. from the University of Michigan Law School, and a B.A. from Vassar College.

Cristóbal De la Maza
Superintendent for the Environment, Government of Chile
Cristóbal de la Maza is Superintendent for the Environment of Chile, directing the lead environmental enforcement agency in the country. He is an industrial civil engineer from Pontificia Universidad Católica de Chile and holds a PhD in Engineering and Public Policy from Carnegie Mellon University. He has worked as a consultant in public and private institutions and was Head of the Division of Information and Environmental Economics at the Ministry for the Environment from 2010 to 2014, where he led the design and implementation of the National Green Growth Strategy. In 2019, he served as Head of the Division of Environment and Climate Change at the Ministry of Energy, where he led the design and implementation of the decarbonization strategy to achieve carbon neutrality by 2050 at a national level. As a researcher, he specialized in engineering, machine learning and judgement and decision-making tools to design policy interventions. During his academic career he has published several articles in specialized journals.

Brian Deese
Managing Director, Global Head of Sustainable Investing. BlackRock
Brian Deese, Managing Director, is Global Head of Sustainable Investing at BlackRock. The Sustainable Investing team is focused on identifying drivers of long-term return associated with environmental, social and governance issues, integrating them throughout Blackrock's investment processes, and creating solutions for our clients to achieve sustainable investment return. Previously, Deese worked in the White House under President Obama where he was the President's senior advisor for climate and energy policy, helping to negotiate the Paris Climate Agreement and other national and international initiatives. Early on in the Obama Administration, he was one of the key architects in the resurgence of the auto industry after the financial crisis. Deese also served as deputy director of the National Economic Council and deputy director of the Office of Management and Budget. Most recently, he has been providing advice to institutions interested in sustainable investing strategies and lecturing at the Kennedy School of Government at Harvard University. He earned a J.D. from Yale Law School, and a B.A. from Middlebury College. He lives in Brookline Massachusetts.

Daniel Esposito
Associate Professor, Department of Chemical Engineering, Columbia University
Daniel Esposito received his Ph.D. in Chemical Engineering at the University of Delaware and studied as a postdoctoral research associate at the National Institute of Standards and Technology (NIST) under a National Research Council fellowship. He is now an Associate Professor in Chemical Engineering at Columbia University, where his group's research interests relate broadly to solar and electrochemical energy conversion. Specific topics of interest include solar fuels, electrocatalysis, photoelectrochemistry, membrane-free electrolyzers, and the use of in situ analytical tools for studying electrocatalytic materials at high spatial and/or temporal resolution.

Julio Friedmann
Senior Research Scholar, Center on Global Energy Policy, Columbia University
Julio Friedmann is a Senior Research Scholar at the Center on Global Energy Policy at Columbia University. He recently served as Principal Deputy Assistant Secretary for the Office of Fossil Energy at the Department of Energy where he was responsible for DOE's R&D program in advanced fossil energy systems, carbon capture, and storage (CCS), CO2 utilization, and clean coal deployment. He has also held positions at Lawrence Livermore National Laboratory, including Senior Advisor for Energy Innovation and Chief Energy Technologist. Friedmann is also the CEO of Carbon Wrangler, LLC, is a Distinguished Associate at the Energy Futures Initiative, and serves as a special advisor to the Global CCS Institute. Friedmann is one of the most widely known and authoritative experts in the U.S. on carbon removal (CO2 drawdown from the air and oceans), CO2 conversion and use (carbon-to-value), and carbon capture and sequestration. His expertise includes technology, policy, and operations.

Michael Gerrard
Professor, Columbia Law School, Columbia University
Michael B. Gerrard is Andrew Sabin Professor of Professional Practice at Columbia Law School, where he teaches courses on environmental and energy law and founded and directs the Sabin Center for Climate Change Law. He is also a member and former Chair of the Faculty of Columbia's Earth Institute. Before joining the Columbia faculty in January 2009, he was partner in charge of the New York office of the Arnold & Porter law firm. He practiced environmental law in New York City full time from 1979 to 2008. He was the 2004-2005 chair of the American Bar Association's Section of Environment, Energy and Resources. He has also chaired the Executive Committee of the New York City Bar Association, and the Environmental Law Section of the New York State Bar Association. He is author or editor of thirteen books, including *Global Climate Change and U.S. Law* (with Jody Freeman) (2d ed. 2014); *Law of Clean Energy: Efficiency and Renewables* (2011); *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal* (with Tracy Hester 2018); and *Legal Pathways to Deep Decarbonization in the United States* (with John Dernbach 2019).

David Goldberg
Professor, Lamont-Doherty Earth Observatory, Columbia University
David Goldberg is a Lamont Research Professor and his interests focus on the integration of different technologies and cross-disciplinary approaches to develop achievable climate solutions. Goldberg received his undergraduate and MS degrees in Earth and Planetary Sciences from the Massachusetts Institute of Technology, and his doctorate in geophysics and an MBA from Columbia University. He conducted post-doctoral studies at the Institute Français du Petrole in Paris and has been at Lamont-Doherty since 1985. He also currently serves as a core faculty member for the Lenfest Center for Sustainable Energy at Columbia and an Associate Director of the Earth Institute's Lamont-Doherty Earth Observatory, Columbia University.

Avril Haines
Senior Research Scholar, Columbia University; Deputy Director, Columbia World Projects
Avril Haines is a Deputy Director of Columbia World Projects, a Lecturer in Law at Columbia Law School, and a Senior Fellow at the Johns Hopkins University Applied Physics Laboratory. She was appointed by President Obama to serve as a Member of the National Commission on Military, National, and Public Service, and serves on a number of boards and advisory groups, including the Nuclear Threat Initiative's Bio Advisory Group, the Board of Trustees for the Vodafone Foundation, and the Refugees International Policy Advisory Council. Prior to joining Columbia University, Haines served as Assistant to the President and Principal Deputy National Security Advisor to President Obama. Before that, she served as the Deputy Director of the Central Intelligence Agency. She also held a number of senior legal positions in the government, including Legal Adviser to the National Security Council. Haines received her bachelor's degree in Physics from the University of Chicago and a law degree from Georgetown University Law Center.

Alex Halliday
Director, Earth Institute; Professor, Department of Earth and Environmental Sciences, Columbia University
Dr. Alex Halliday is the Director of Columbia University's Earth Institute. He joined the Earth Institute in April 2018, after spending more than a decade at the University of Oxford, during which time he was the dean of science and engineering. With about 400 published research papers, Halliday has been a pioneer in developing mass spectrometry to measure small isotopic variations in objects as different as meteorites and living organisms, helping to shed light on the birth and early development of our solar system, the interior workings of the Earth, and the processes that affect Earth's surface environment. His scientific achievements have been recognized through numerous awards, including the Murchison Medal of the Geological Society, the Bowen Award and Hess Medal of the American Geophysical Union, the Urey Medal of the European Association of Geochemistry, and the Oxburgh Medal of the Institute of Measurement and Control. He is a Fellow of the UK's Royal Society and Foreign Associate of the US National Academy of Sciences. His contributions to science and innovation have been recognized with the award of a knighthood in the UK.

Halliday has also helped to lead a variety of distinguished scientific societies and advisory panels. He is the former Vice President of the Royal Society and former President of the Geochemical Society. He has served as an external board member for Britain's Natural Environment Research Council, the Max Planck Society, London's Natural History Museum, the American Geophysical Union, Carnegie Science and more. As a professor in Columbia's Department of Earth and Environmental Sciences, Halliday divides his time between Columbia's Morningside campus and his geochemistry lab at Lamont-Doherty Earth Observatory.

Geoffrey Heal
Donald C. Waite III Professor of Social Enterprise, Columbia Business School

Geoffrey Heal is noted for contributions to economic theory and resource and environmental economics. He holds bachelors and doctoral degrees from Cambridge University and an Honorary Doctorate from the Universite´ de Paris Dauphine. He is Donald Waite III Professor of Social Enterprise at Columbia's Graduate School of Business. Author of eighteen books and over two hundred articles, he is a Member of the National Academy of Sciences, a Fellow of the Econometric Society, Past President of the Association of Environmental and Resource Economists, recipient of its prize for publications of enduring quality and Life Fellow, a Director of the Union of Concerned Scientists, a founder, Director and Chairman of the Board of the Coalition for Rainforest Nations and a member of the economic advisory board of the Environmental Defense Fund.

Heal chaired a committee of the National Academy of Sciences on valuing ecosystem services, was a Commissioner of the *Pew Oceans Commission*, an IPCC coordinating lead author for the fifth assessment report, a member of President Sarkozy's *Commission on the Measurement of Economic Performance and Social Progress* and of the advisory board for the World Bank's 2010 *World Development Report* and UNEP's 2011 *Human Development Report*. He is currently a member of an OECD high-level experts group on the measurement of national income and a UNFCCC high-level group making recommendations about the implementation of the 2015 Paris climate accord. He has been a principal in two startup companies and on the investment committee of a green private equity group. Recent books include *Nature and the Marketplace*; *Valuing the Future*; *When Principles Pay*; and *Endangered Economies: How the Neglect of Nature Threatens Our Prosperity*.

Marie Johansson
Director of Product Sustainability, Colgate-Palmolive Company

Marie Johansson is the Director of Product Sustainability for Colgate-Palmolive Company, a consumer products company based in New York City. She is responsible for the leadership of Colgate's global product sustainability program. In addition, she leads the stewardship committee on ingredients selection in addition to external programs with retailers and other stakeholders. She is also a key leader for the Colgate-Palmolive consumer transparency program. Johansson has contributed to Colgate for 22 years in various roles in Research & Development and Supply Chain. She holds a M.S. in Analytical Chemistry from Lund University, Sweden and a Ph.D. in Chemistry from Lehigh University. Johansson is Colgate-Palmolive's representative on the National Academies of Sciences Roundtable for Environmental Health and as Global Partner for the Society of Environmental Toxicology and Chemistry.

Noah Kauffman
Research Scholar, Center on Global Energy Policy, Columbia University
Noah Kaufman joined the Center on Global Energy Policy as research scholar in January 2018. He is an economist who has worked on energy and climate change policy in both the public and private sectors. Under President Obama, he served as the Deputy Associate Director of Energy & Climate Change at the White House Council on Environmental Quality. Kauffman received his BS in economics from Duke University and his PhD and MS in economics from the University of Texas at Austin, where his dissertation examined optimal policy responses to climate change.

Richard Kauffman
Chair, New York State Energy Research & Development Authority
Richard Kauffman is Chairman of the New York State Energy Research and Development Authority (NYSERDA). He also serves as Chair of Generate Capital, a leading financier of clean energy projects. Prior to these roles, Kauffman served in the Executive Chamber of Governor Andrew M. Cuomo as New York State's first "Energy Czar". As "Czar," he led the State's Reforming the Energy Vision (REV) policy. He oversaw the State's energy agencies, including the Department of Public Service, the New York Power Authority, the Long Island Power Authority, NYSERDA and the York Green Bank He previously served as Senior Advisor to U.S. Secretary of Energy Steven Chu and in senior roles in finance, including as partner at Goldman Sachs.

Jason Klein
Vice President, US Energy Transition Strategy at Shell
Jason Klein is responsible for Shell's US Energy Transition Program, which involves assessing emerging risks and opportunities across Shell's US businesses from the global transition to lower carbon energy; developing policy and advocacy positions around energy transition in the US; and implementing long-term strategies to make Shell resilient to expected changes in the energy system and allow Shell's US businesses to thrive as the world moves to lower-carbon energy. Klein joined Shell following the acquisition of BG Group, where he was Asset General Manager for BG in the United States. A lawyer by background, Klein joined the BG Group's legal team in 2003, where he had senior legal roles in the US, UK, Oman and Australia, including serving as BG's Deputy General Counsel in both Houston and London. A native Houstonian, he earned a BSc in Finance from Trinity University in San Antonio and a doctorate of jurisprudence from the University of Texas School of Law.

Nicholas Lemann
Director, Columbia World Projects; Director, Columbia Global Reports; Joseph Pulitzer II and Edith Pulitzer Moore Professor of Journalism; Dean Emeritus of the Faculty of Journalism
Nicholas Lemann directs Columbia World Projects. He also directs Columbia Global Reports, a book publishing venture that presents reporting around the globe on a wide range of political, financial, scientific, and cultural topics. Lemann is Dean Emeritus and Pulitzer Moore Professor of Journalism at Columbia. During his deanship, the Journalism School completed its first

capital fundraising campaign, started its first new professional degree program since the 1930s, and launched significant initiatives in investigative reporting, digital journalism, and executive leadership for news organizations. Board memberships include Columbia's Knight First Amendment Institute and the Russell Sage Foundation. Lemann is a member of the New York Institute for the Humanities and the American Academy of Arts and Sciences, and a staff writer for *The New Yorker*.

John Lochner
Vice President Innovation, New York State Energy Research and Development Authority (NYSERDA)
John Lochner founded Headland Advisors, which advises on and structures investments in sustainability-focused opportunities. As an investor in and advisor to businesses in water, energy, and sustainable resource management, he formerly served in leadership and advisory positions at Natural Resources Defense Council and Locus Energy. His experience in renewable energy includes work as a consultant to the Department of Energy, as a Board member, Treasurer, and Member of the Executive Committee of the Solar Energy Finance Association (SEFA), and as an investment banker in the Global Energy Group at Credit Suisse, where Lochner executed transactions across the traditional and renewable power sectors. He is a graduate of Duke University and received an MA from Harvard University and an MBA from The Wharton School of the University of Pennsylvania.

Christoph Meinrenken
Associate Research Scientist, Earth Institute, Engineering School, Data Science Institute, Columbia University
Christoph Meinrenken is an Associate Research Scientist at Columbia University's Earth Institute, adjunct assistant professor in the Department of Earth and Environmental Engineering, and affiliate of the Foundations of Data Science Center at the Data Science Institute. His research focuses on computer modeling to elucidate and improve the techno-economic performance of low carbon energy systems. Recent and current research projects include demand management and energy storage in smart buildings (DoE, NSF, NYSERDA, NIST), electrification of the transportation sector, synthetic fuels (ABB, Electricity de France), and automated product carbon footprinting (PepsiCo Inc.). An expert in Life Cycle Assessment and enterprise-scale product analytics, Meinrenken has worked with the World Resources Institute, Carbon Disclosure Project (CDP), and The Sustainability Consortium, and consulted several globally operating consumer goods manufacturers. Before joining Columbia, Meinrenken worked on modeling molecular spectra (MSE, Princeton University, 1996) and computational neuroscience (PhD Physics, Max Planck Institute, 2001). In addition to academic research and teaching, Meinrenken spent several years in the private sector, specializing in financial engineering and risk management.

Vijay Modi

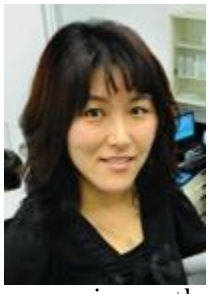
Professor of Mechanical Engineering, Columbia University; Affiliate, Earth Institute and Data Science Institute; Director, Sustainable Engineering Laboratory

Vijay Modi's areas of expertise are energy resources/access, energy planning for access and renewable integration, demand estimation and role of novel payment systems in breaking barriers to upfront costs. His laboratory, the Quadracci Sustainable Engineering Lab (QSEL), has been responsible for innovations such as a low-cost lead-acid charge/discharge circuit for solar lanterns (2005), fully digital pay-as-you-go minigrids that have been continuously operating as pilots since 2011, battery-less PAYG smallholder irrigation systems (2013-15) and widely used tools such as "Network Planner" for making technology choices under demographic, demand and geographic variations. His recent work has been on energy infrastructure design and planning; solar energy; energy efficiency in agriculture, and data analytics spanning from urban settings to remote rural settings. He is currently working to understand how energy services can be more accessible, more efficient and cleaner and examining minigrids in the context of energy efficiency

Bruce Nilles

Managing Director, Rocky Mountain Institute

Bruce Nilles is a Managing Director at Rocky Mountain Institute where he is leading its work on electrifying everything with clean electricity, starting with the building sector. Over the past 15 years Bruce helped build and lead the Sierra Club's Beyond Coal Campaign, a nationwide effort to replace coal with clean energy. He holds undergraduate and law degrees from the University of Wisconsin in Madison and spent the first four years of his career at the U.S. Department of Justice Environment and Natural Resources Division. He is the 2018 recipient of the Packard Foundation Climate Breakthrough Award. Nilles currently resides in Oakland, California with his wife and two children and enjoys running among the redwoods whenever he can find the time.



Alissa Park

Earth and Environmental Engineering & Chemical Engineering, Columbia University; Lenfest Associate Professor in Applied Climate Science, Lenfest Center for Sustainable Energy

Alissa Park is the Lenfest Chair in Applied Climate Science of Earth and Environmental Engineering & Chemical Engineering at Columbia University. She is also the Director of the Lenfest Center for Sustainable Energy at the Earth Institute. Her research focuses on sustainable energy conversion pathways with emphasis on integrated carbon capture, utilization and storage (CCUS). The current efforts include the fundamental studies of chemical and physical interactions of natural and engineered materials with CO2 such as the development of novel

nano-scale hybrid materials for integrated CO2 capture and conversion. Founded on these new materials and reaction schemes, the Park group is also working on innovative fuel synthesis pathways and fluidized bed reactor designs using unconventional energy sources such as shale gas, biomass and municipal solid wastes, while minimizing environmental impacts. Park received a number of professional awards and honors including the NSF CAREER Award (2009), James Lee Young Investigator Award (2010), American Chemical Society WCC Rising Star Award (2017), Janette and Armen Avanessians Diversity Award at Columbia University (2017), International Partnership Award for Young Scientists of Chinese Academy of Sciences (2018), American Chemical Society Energy and Fuels Division - Emerging Researcher Award (2018), PSRI Lectureship Award in Fluidization at American Institute of Chemical Engineers (2018), and U.S. C3E Research Award (2018). Park was also the Chair of the CO2 Utilization Area for the Mission Innovation Workshop on Carbon Capture, Utilization and Storage held in September 2017.

John Podesta
Founder and Director, Center for American Progress
John Podesta served as Chair of Hillary for America. Prior to joining Hillary Clinton's campaign, he served as Counselor to President Barack Obama. In 2008, he served as co-chair of President Obama's transition team, where he coordinated the priorities of the incoming administration's agenda, oversaw the development of its policies, and spearheaded its appointments of major cabinet secretaries and political appointees. He is the former Chair of the Washington, D.C.-based think tank Center for American Progress and the Center for American Progress Action Fund. Prior to founding the Center in 2003, Podesta served as White House Chief of Staff to President William J. Clinton. He also recently served on the President's Global Development Council and the UN Secretary General's High-Level Panel of Eminent Persons on the Post-2015 Development Agenda. Additionally, Podesta has held numerous positions on Capitol Hill, including counselor to Democratic Leader Sen. Thomas A. Daschle (1995-1996). A Chicago native, Podesta is a graduate of Knox College and the Georgetown University Law Center, where he is currently a visiting professor of law.

Kenneth Prewitt
Carnegie Professor of Public Affairs, Columbia University;
Special Advisor to the President
Kenneth Prewitt is the Carnegie Professor at the School of Public Affairs at Columbia University, and Advisor to its President on the university's 21st century ambitions, including Columbia World Projects. Previous positions include faculty, U. of Chicago; President, Social Science Research Council; Senior Vice President, Rockefeller Foundation; and Director, U.S. Census Bureau. He serves on numerous social science boards and advisory committees. His current research focuses on research universities and the science policy necessary for their well-being.

Karen Reif

Vice President, Renewables and Energy Solutions, Public Service Electric & Gas Company

Karen Reif was elected vice president - renewables and energy solutions, effective July 2018. In this role she oversees PSE&G's clean energy strategy. She is responsible for the operations and strategic growth of both PSE&G and PSEG Long Island's solar energy, energy efficiency, demand response and alternative fuel vehicle programs. As of July 2018, PSE&G has made more than $1.3 billion in solar investments in New Jersey and more than $400 million in energy efficiency programs in the state. PSE&G's current Solar 4 All investment is concentrating on turning landfills and brownfields green by building solar farms on otherwise unusable sites. In addition, the company has announced plans to propose an additional $2.5 billion in energy efficiency programs, $300 million in electric car infrastructure investment and $100 million in battery storage projects. Previously, Reif was senior director of continuous improvement for the Shared Services Organization at PSEG. She established this function for PSEG, which is responsible for developing sustainable, repeatable and quantifiable business improvements based on industry best practices. Reif has been with PSEG since 1995 and spent 14 of those years in the Information Technology Department. She worked in multiple areas of IT holding several leadership roles. Areas of focus included finance, strategy, business relationship, application implementation, quality assurance, process management and program management. Prior to joining PSEG, she was a consultant with Scott, Madden & Associates. Reif holds a BA in Economics and International Studies from Emory University and a MBA (MSIA) from Carnegie Mellon University. She has the following certifications: Project Management Professional, Lean Six Sigma, and Information Technology Infrastructure Library (ITIL) Foundation.

Andrew Revkin

Founding Director, Initiative on Communicaton and Sustainability, Earth Institute, Columbia University

Andrew Revkin is the Founding Director of the Initiative on Communication and Sustainability at the Earth Institute and serves on the Executive Committee for Research and Exploration of the National Geographic Society. Revkin has spent 35 years in environmental and science journalism, including, most recently, senior positions at *National Geographic* and *ProPublica*. From 2010 through 2016, he taught at Pace University and wrote his Dot Earth blog for the Opinion section of The *New York Times*. He was a reporter for the paper from 1995 through 2009. Revkin, who began writing on climate change in the 1980s, has won most of the top awards in science journalism, along with a Guggenheim Fellowship, Columbia University's John Chancellor Award for sustained journalistic excellence and an Investigative Reporters & Editors Award. He has written books on the history of weather and climate knowledge, global warming, the changing Arctic and the assault on the Amazon rain forest, as well as three book chapters on science communication.

David Sandalow
Inaugural Fellow, Center on Global Energy Policy; Senior Research Scholar, Columbia University
David Sandalow is the Inaugural Fellow at the Center on Global Energy Policy and co-Director of the Energy and Environment Concentration at the School of International and Public Affairs at Columbia University. He founded and directs the Center's U.S.-China Program. During Fall 2018, he was a Distinguished Visiting Professor in the Schwarzman Scholars Program at Tsinghua University. Sandalow has served in senior positions at the White House, State Department and U.S. Department of Energy. He came to Columbia from the U.S. Department of Energy, where he served as Under Secretary of Energy (acting) and Assistant Secretary for Policy & International Affairs. Prior to serving at DOE, Mr. Sandalow was a Senior Fellow at the Brookings Institution. He has served as Assistant Secretary of State for Oceans, Environment & Science and a Senior Director on the National Security Council staff. Sandalow writes and speaks widely on energy and climate policy. Recent works include *Electric Vehicle Charging in China and the United States* (February 2019, co-author), *Direct Air Capture of Carbon Dioxide Roadmap* (December 2018, project chair), *Guide to Chinese Climate Policy* (July 2018), *A Natural Gas Giant Awakens* (June 2018, co-author), *The Geopolitics of Renewable Energy* (2017, co-author), *Financing Solar and Wind Power: Lessons from Oil and Gas* (2017, co-author), *CO2 Utilization Roadmap 2.0* (2017, project chair) and *The History and Future of the Clean Energy Ministerial* (2016). Other works include *Plug-In Electric Vehicles: What Role for Washington?* (2009) (editor), *U.S.-China Cooperation on Climate Change* (2009) (co-author) and *Freedom from Oil* (2008).

Abe Silverman
General Counsel, New Jersey Board of Public Utilities
Abe recently joined the BPU after working in the energy space for 20 years, including working at FERC, private practice, and for the last decade, NRG Energy, Inc.

Nik Steinberg
Forum Director, Columbia World Projects
Nik Steinberg is the Forum Director at Columbia World Projects. He previously served as the Counselor and Chief Speechwriter for Amb. Samantha Power, U.S. Ambassador to the United Nations. Prior to that, Steinberg was Senior Researcher in the Americas Division of Human Rights Watch, where his work focused primarily on Mexico and Cuba. He is a graduate of Dartmouth College and the Harvard Kennedy School of Government.

Dan Steingart

Associate Professor Chemical Metallurgy and Chemical Engineering, Columbia University

Daniel Steingart is the Stanley Thompson Associate Professor of Chemical Metallurgy and Chemical Engineering and the co-director of the Columbia Electrochemical Energy Center. His group studies the systematic behaviors of material deposition, conversion, and dissolution in electrochemical reactors with a focus on energy storage devices. Steingart's current research looks to exploit traditional failure mechanisms and unwanted interactions in batteries, turning unwanted behaviors into beneficial mechanisms. His efforts in this area over the last decade have been adopted by various industries and have led directly or indirectly to five electrochemical energy related startup companies, the latest being Feasible, an effort dedicated to exploiting the inherent acoustic responses of closed electrochemical systems. He joined Columbia Engineering in 2019 from Princeton University where he was an associate professor in the department of mechanical and aerospace engineering and the Andlinger Center for Energy and the Environment. Earlier, he was an assistant professor in chemical engineering at the City College of the City University of New York. Even earlier he was an engineer at two energy related startups. He received his PhD from the University of California, Berkeley, in 2006.

Satya Tripathi

Assistant Secretary General and Head of the New York Office, United Nations Envrionment Programme

Satya S. Tripathi is UN Assistant Secretary-General and Head of New York Office at UN Environment. A development economist and lawyer with over 35 years of varied experience, Mr. Tripathi has served with the UN since 1998 in key positions in Europe, Asia and Africa in the areas of Climate Change, Human Rights, Democratic Governance and Legal Affairs. He was Chair of the Committees on Laws, Treaties and Administrative matters for the UN-mediated Cyprus unification talks in 2004; UN Recovery Coordinator for Aceh and Nias where he facilitated international cooperation and funding of over US$ 7 billion for post-tsunami and post-conflict recovery efforts in support of the Indonesian government and affected populations; and Executive Head of UNORCID, a UN System Office of 10 UN Agencies established by the UN Secretary General in 2011 to facilitate the implementation of a US$ 1 Billion REDD+ partnership between Indonesia, Norway and other stakeholders on climate change mitigation and adaptation through the conservation of forests and preservation of peat-land and bio-diversity. Mr. Tripathi was instrumental in establishing the Tropical Landscapes Finance Facility (TLFF) in Indonesia in 2016 and the Sustainable India Finance Facility (SIFF) in 2017 to leverage 'private finance for public good' at mega-scale to achieve transformative social and environmental impact in developing countries. He previously served on the World Economic Forum's Global Advisory Council on Forests; and in India as a member of its national civil service.

Venkat Venkataraman

EVP of Engineering and Chief Technology Officer, Bloom Energy

Venkat Venkataraman brings to Bloom Energy more than 35 years of experience in process design and optimization. He leads the development of highly efficient and low cost Bloom Energy Servers. During his tenure at Bloom, he led the company through many technological breakthroughs bringing SOFC technology from early stages of development to a very matured state enabling deployment of highly efficient commercial systems. Over the years, Venkat has assembled, led and mentored a very strong team of engineers and innovators around the world in the areas of stack technology, system integration and power electronics, who have made tremendous strides in that time, solving the key technical challenges that had previously prevented the commercialization of SOFC technologies. He has authored/co-authored several patents in the areas of SOFC technology, fuel processing, heat integration and control systems. Prior to joining Bloom Energy, Venkat was a Principal Technologist at Aspen Technology, Inc. where he led the commercial development of high end design, simulation and optimization software for the chemical and petrochemical industries. Venkat is a winner of AIChE award in the area of chemical process optimization, and holds a Ph.D in chemical engineering from Clarkson University.

Alan West

Professor, SEAS, CEEC, Columbia University

Alan West received his PhD in Chemical Engineering from the University of California and his BS from Case Western Reserve University. He is the co-director of the Columbia Electrochemical Energy Center and is the Samuel Ruben-Peter G. Viele Professor of Electrochemistry, with appointments in the Department of Chemical Engineering and the Department of Earth and Environmental Engineering. His research interests include batteries, electrochemical synthesis, and fuel cells.