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HEARING ON: BUILDING A 100 PERCENT CLEAN ECONOMY: PATHWAYS TO NET ZERO INDUSTRIAL EMISSIONS

WRITTEN TESTIMONY:

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Introduction

Thank you, Chairman Tonko, Ranking Member Shimkus and Members of the Sub-Committee for inviting me to appear before you as you review and examine pathways to address the emissions of carbon dioxide (CO_2) from heavy industry operations. Herein, I encompass the definition of heavy industry broadly, e.g., to include sectors including oil and gas refining, petrochemical and chemicals production industries, and cement, steel and glass production; amongst others. As requested by the sub-committee, I am focusing my testimony on opportunities, pathways, and solutions to address the emissions of carbon dioxide (CO_2) from heavy industry. This includes, for example, pioneering research initiatives that are underway at UCLA's Institute for Carbon Management [] that seek to specifically enable heavy industry to mitigate its carbon emissions, and thereby adapt, expediently, and cost-effectively, to a low-carbon world. The views expressed herein are my own, and do not necessarily represent those of UCLA.

For reference: I am a Professor and Henry Samueli Fellow in the Samueli School of Engineering at the University of California, Los Angeles (UCLA), where I am the Director of the Institute for Carbon Management [[1]]. I am a civil engineer, and a materials scientist with broad competencies in materials synthesis, characterization and processing with special expertise in the materials of modern construction including: cement, concrete, steel, glass and ceramics [[2]].

Summary: My testimony today encompasses the key sections that are outlined below:

Motivation: Heavy industry operations which result in the manufacture and production of materials and products including: cement and concrete, glass, liquid fuels, steel, etc. are foundational to the world that we live in. From the automobiles that we drive, to the buildings that we live, and work in, to the (smart) screens of our personal handheld devices, heavy industry operations affect, and improve the quality of each of our lives, while contributing to ongoing, and continuous developments of our society as a whole.

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[1] Institute for Carbon Management. UCLA ICM http://icm.ucla.edu/ (accessed Sep 12, 2019).
[2] Gaurav N. Sant. Google Scholar Profile https://scholar.google.com/citations?user=p_kytiYAAAAJ&hl=en&oi=ao (accessed Sep 12, 2019).

While invaluable, heavy industry operations, either on account of their processing energy demands, and/or the nature of chemical separations, modifications, and transformations that they seek to carry out result in substantial emissions of carbon dioxide into the atmosphere. For example, worldwide, chemical and petrochemical processing, the production of cement (ordinary portland cement, OPC), and iron and steel production result in the emission of around 5 % [3], 10 % [3], and 9 % [3] of anthropogenic CO_2 emissions, respectively. Carbon dioxide emissions from heavy industry – cumulatively amounting to nearly 36 % of global emissions [4] – are particularly difficult to address because, often, switching energy sources from fossil-based to renewable energy generation (i.e., a potential pathway to reduce the carbon intensity of industrial operations) may be infeasible on account of the: (a) insufficient energy density of typical renewable energy sources [5], and/or (b) 24/7 nature of manufacturing operations [6]. While energy storage approaches would indeed assist in enabling and improving the integration of renewable energy into powering heavy industry operations, the substantial cost of deploying energy storage (currently), renders this option challenging for the vast majority of heavy-industry sectors. Often, in processes such as oil refining, cement production and others – feedstocks are broken down into simpler components, before being re-composed into more chemically, and commercially desirable products such as gasoline, and OPC. Thus, in such operations, a majority of the carbon burden is associated with the chemical route that is chosen; e.g., in the case of OPC production [7] the thermal decomposition of limestone ($CaCO_3$) and the associated release of CO_2 is a far more significant contributor to the carbon emissions of the process than the combustion of fuel to heat the kiln [8]. It should be furthermore noted, the emplacement of heavy industry manufacturing facilities requires substantial capital expenditures, and therefore, demands long amortization periods. Since new capital investments may be difficult to justify, it is necessary that carbon management technologies, ideally, “bolt-on” to large intensive CO_2 emitters and furthermore make use of waste heat, if available, to reduce energy burdens. These considerations may be helpful, even partially so, to accelerate new technology commercialization and deployment.

Unquestionably, decarbonizing heavy industry is a critical need to mitigate the accumulation and release of CO_2 into the atmosphere; a key driver of climate change. However, such decarbonization on account of both, being technically challenging and our societal dependency on these industries, needs to be implemented speedily, without dramatically disrupting the material contributions of these sectors to our way of life. Thus, it is important to stage, support, and incentivize the transformations of these sectors from being valuable contributors, and major CO_2 emitters, to exclusively valuable contributors by 2050.

Enabling and empowering the decarbonization of heavy industry: Decarbonization as we understand it, at the scales that it is needed to abate climate altering carbon emissions, is often taken to imply carbon capture and storage (CCS) [9]. While unquestionably CCS remains the preeminent route to address CO_2 emissions at a sufficient scale, globally, this approach is not inconsequential to implement. For example, CCS is not always viable due to: (i) its high cost, (ii) uncertainty associated with the permanence of the sequestration solution, and/or, (iii) the lack of suitable geological features, or logistics facilities to convey

[3] International Energy Agency. Tracking Clean Energy Progress: Industry https://www.iea.org/tcep/industry/ (accessed Sep 12, 2019).
[4] International Energy Agency. CO2 Emissions Statistics https://www.iea.org/statistics/co2emissions/ (accessed Sep 12, 2019).
[5] de Pee, A.; Pinner, D.; Roelofsen, O.; Somers, K.; Speelman, E.; Witteveen, M. *Decarbonization of Industrial Sectors: The Next Frontier*; McKinsey & Company, 2018; p 63.
[6] International Energy Agency; Cement Sustainability Initiative. *Technology Roadmap: Low-Carbon Transition in the Cement Industry*; World Business Council for Sustainable Development, 2018; p 66.
[7] The production of ordinary portland cement (OPC) – the primary binding agent used in traditional concrete – accounts for nearly 9% of global CO2 emissions with 0.9 t of CO2 being emitted per ton of OPC produced. Therefore, the development of new cementation agents that take-up CO2 is critical to reduce the CO2 emissions associated with cement/concrete production,
[8] International Energy Agency; Cement Sustainability Initiative. *Technology Roadmap: Low-Carbon Transition in the Cement Industry*; World Business Council for Sustainable Development, 2018; p 66.
[9] In traditional carbon capture and storage (CCS), CO_2 emitted from industrial processes or from the combustion of fossil fuels is first concentrated to >95 % purity, following which it is transported by pipelines to locations that it can be geologically disposed, e.g., in hydrocarbon depleted reservoirs, saline aquifers, etc.

CO_2 to locations where CCS can be achieved [4,10,11]. This is especially relevant for heavy industry sectors – which broadly speaking, on account of their commodity products, and consequent low-profit margins are poorly equipped, financially speaking, to implement dramatic capital expenditure intensive transformations in an accelerated manner. Therefore, it is necessary to curate a multiplicity of short-, medium- and longer-term pathways empowered by: research, development, and technology deployment and piloting support, explicit financial incentives that promote industrial transformations, and strategic procurement actions; i.e., which involves the preferred sourcing of products, not only on the basis of (lowest) cost, but both cost and embodied carbon intensity [12]. Of course, the basis of each of these actions is: credible policy, regulatory certainty, and national motivation to transition the U.S. economy to a low-carbon/net-zero paradigm.

Over the past several years, federal R&D support provisioned to UCLA has been foundational to the curation of pioneering CO_2 removal/utilization technologies that upcycle dilute-state CO_2 (e.g., secured from industrial flue gases, or the atmosphere) – via thermodynamically favorable mineralization reactions – into stable carbonate compounds. This approach of single-step/integrated carbon capture, utilization and storage (CCUS) is significant as the stable carbonates thus produced can form: (a) CO_2Concrete-based construction materials and components that are cost- and functionally-equivalent to traditional concrete albeit with an embodied carbon intensity (eCI) which is up to 75 % lower [13,14,15,16], and/or (b) solid wastes, e.g., in the form of sand and stone, that could be disposed on the earth's surface, or repurposed in construction thereby reducing the need for geological (CO_2) disposal [17]. However, and in spite of the progress made (e.g., a pilot-system of the CO_2Concrete process will be demonstrated at two coal power plants in 2020 [18]); the industrial deployment of solutions of this nature requires further confidence building and greater support. This is necessary, for example, to allow the cement/OPC industry to gain confidence in the scalability, cost-effectiveness, and the technology's potential to offer a reduced CO_2 trajectory for concrete production. Thus, in the short-term, government support is critical to upscale and demonstrate mineralization technologies such as CO_2Concrete, and other pathways which seek to transform CO_2, at gigaton scales into benign wastes, or saleable products; or that seek to otherwise abate the CO_2 emissions from industrial processes. But, beyond enabling technology developers (N.B.: for a successful model of this nature see the Department of Energy's Carbon Capture Program [19]), early-stage incentives also need to motivate corporations to deploy, trial and integrate new CO_2 abatement technologies into existing operations. Such motivation and commercialization support may take one of many forms including: direct incentives (e.g., financial grants in support of process modifications and improvements), tax credits, or other support structures or even seek to impose (carbon) tax obligations.

First, timely action to mitigate the effects of climate change requires the deployment, de-risking and demonstration of new technologies, in the short-term (<5 years), that can help heavy industry mitigate

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[10] Kulichenko, N.; Ereira, E. *Carbon Capture and Storage in Developing Countries: A Perspective on Barriers to Deployment*; Energy and Mining Sector Board Discussion Paper, No. 25; World Bank Publications, 2012.
[11] Bachu, S. *Energ. Convers. Manage.* **2000**, *41* (9), 953–970.
[12] Bonta, R.; Eggman, S.; Steinorth, M. Assembly Bill 262 - Buy Clean California Act; 2017.
[13] Vance, K.; Falzone, G.; Pignatelli, I.; Bauchy, M.; Balonis, M.; Sant, G. *Ind. Eng. Chem. Res.* **2015**, *54* (36), 8908–8918.
[14] Wei, Z.; Wang, B.; Falzone, G.; La Plante, E. C.; Okoronkwo, M. U.; She, Z.; Oey, T.; Balonis, M.; Neithalath, N.; Pilon, L.; et al. *J. CO_2 Util.* **2018**, *23*, 117–127.
[15] Mehdipour, I.; Falzone, G.; La Plante, E. C.; Simonetti, D.; Neithalath, N.; Sant, G. *ACS Sustain. Chem. Eng.* **2019**, *7* (15), 13053–13061.
[16] CO_2Concrete: https://www.co2concrete.com/ (accessed Sep 12, 2019)
[17] The production of solid carbonates including calcite and magnesite exploits favorable thermodynamics and produces stable mineral reaction products that are known to persist at ambient temperature and pressure, without risk of CO_2 leakage, or release over billions of years. Furthermore, the handling of solid mineral carbonates, i.e., as compared to fluid-state CO_2 is simpler and presents distinct advantages, including existing and highly cost-effective infrastructure (e.g., as used today for municipal waste disposal), and a comprehensive understanding of the economics of such surficial disposal.
[18] DOE National Energy Technology Laboratory. A Scalable Process for Upcycling Carbon Dioxide (CO_2) and Coal Combustion Residues Into Construction Products https://netl.doe.gov/project-information?p=FE0031718 (accessed Sep 12, 2019).
[19] DOE National Energy Technology Laboratory. Carbon Capture Program https://www.netl.doe.gov/coal/carbon-capture (accessed Sep 12, 2019).

its carbon emissions. However, the deployment of such technologies, requires a combination of strategic actions; e.g., government support of technology demonstration projects, and industry partnerships so that the lessons learned hasten, motivate and inform further deployments, drive cost-reductions and therefore, accelerate technology diffusion and adoption. Why? Because commodity sectors (i.e., an identification that is typical for heavy industry) which will not be offshored – e.g., cement/OPC production, oil refining, etc. – feature little, if any appetite for deploying new technologies that are unproven at scale due to: uncertainty in revenue, profit pressures, prevailing and substantial regulatory and compliance burdens, and the very high costs associated with emplacing greenfield facilities with long operating horizons. Therefore, it is necessary for the government to underwrite the costs associated with maturing, and de-risking technologies which can help heavy industries to reduce the eCI of their products, and processes. However, once industry is assured of the viability and scaling of new technologies; this greatly simplifies and accelerates subsequent market penetration, and diffusion.

Second, in the medium- and longer-term it is critical that the government greatly expand research, development, deployment and innovation (RDDI) funds – encompassing both basic and applied research – that will create transformational carbon (CH_4 and CO_2) removal and utilization technologies (e.g., see recent reports developed by the National Academies [[20],[21]]). Such support forms the basis of developing newer, more efficient and more effectively scalable technologies for carbon emissions mitigation; the need for which becomes increasingly more significant with the passage of time [[22]]. Major programs for the development, de-risking and deployment of the next generation of technologies, including CCUS (carbon capture, utilization, and storage) solutions enabled via support provisioned by the Departments of Defense, Energy, Transportation, Housing and Urban Development, and, National Science Foundation amongst others is critical to maintain the U.S.'s intellectual leadership in the broad theme of carbon management. This is needed to: (a) ensure that U.S. corporations are able to monetize and diffuse their spirit of creativity, innovation and societal welfare, globally, (b) ensure that U.S. corporations are able to diminish the intensity of their operations, thereby enabling them to operate across global jurisdictions in a low-carbon world, and (c) ensure that the U.S.'s deep intellectual reservoir that is housed within its world-class universities, national laboratories and corporate R&D organizations continues to train, sustain, support and grow the talented scientists, engineers and subject matter experts that have ensured the U.S.'s global technological leadership, and spirit of innovation over nearly the last century.

Major, long-term, and comprehensive actions by heavy industry in support of rationalizing and reducing their CO_2 emissions intensity are assured to require substantial capital expenditures. While this will also (likely) affect the operating cost bases of such sectors; clarity and commitments to making such capital expenditures requires certainty regarding upcoming regulations, and policy. Unquestionably, our current state of regulatory uncertainty is perhaps the most significant detriment that prevents, or otherwise hinders our collective capability to limit the emissions of CO_2 into the atmosphere. The reasoning is simple: first, corporations which owe, on the basis of today's prevalent although evolving business model, to create value for shareholders are only going to make decisions and selections which ensure a competitive advantage in the marketplace. Therefore, unless heavy industry processes and products are brought under a CO_2 limiting ambit (e.g., a carbon emissions cap; and a consequent penalty for unbounded excess; see also California's Assembly Bill 32 [[23]]); there is no incentive, or lack thereof to make investments that would reduce the carbon intensity of these industries. It may be argued, that strategic actions, i.e., governmental purchasing decisions that prefer low-carbon products may be equally valuable. Unquestionably this is so and should be pursued aggressively – however, many examples belie

[20] National Academies of Sciences, Engineering, and Medicine. *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*; The National Academies Press: Washington, DC, 2018; p 254.

[21] National Research Council. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*; The National Academies Press: Washington, DC, 2015; p 154.

[22] Mercator Research Institute on Global Commons and Climate Change (MCC). Remaining carbon budget https://www.mcc-berlin.net/en/research/co2-budget.html (accessed Sep 12, 2019).

[23] Nunez, F.; Pavley, F. *Assembly Bill 32 - California Global Warming Solutions Act of 2006*; 2006.

the proof that the most substantial successes come about by affecting supply chains holistically; i.e., both upstream and downstream: i.e., from the point of raw material procurement, to the point of finished product consumption. This raises an important point that was previously alluded to: we, society in general, are the consumers of the products (and thereby processes) that heavy industry implements. As such, an important aspect of carbon management involves affecting consumer choices, selections, and awareness regarding the products that we seek to consume. This issue whose success is seen in our implementations of energy efficiency programs – requires us to develop a national basis of measuring, affecting and incenting carbon efficiency via robust, progressive, and transparent methods of analysis. The reason: small changes affected by, and demanded by 330 million consumers (citizens) in the U.S., and 7 billion consumers, globally, would result in vast CO_2 emissions reductions that are motivated by both "industry-push and market-pull". Simultaneous actions of this manner undertaken by governments, corporations, consumers, and markets are foundational to create a non-villainized basis of ensuring major industrial transformations from producer to consumer; i.e., a market-driven basis of change.

It is particularly important to highlight that issues related to carbon management are based on the premise of affecting societal good. This is an outcome in which, national governments, more than any other (private) entity have a vested interest. Therefore, it is necessary that governments take action in this regard. The U.S. plays a special role in this international effort. Because, over the last century or so, the U.S. has come to be regarded as the bellwether for the future; such that directions implemented by the U.S. are legitimized and thus easier to implement for other national governments, worldwide. Of interest, the U.S. contributes nearly 15 % of global CO_2 emissions, while hosting only 5 % of the world's population [[24]]. For reasons of leading by example, it is essential that the we place emphasis on robustly maximizing our carbon efficiency, and in turn, diminishing our CO_2 emissions intensity.

The role of incentives and market mechanisms: Reducing, limiting and reversing CO_2 emissions, from heavy industry, and other sectors requires the development and broad-based deployment of incentives, disincentives, and market-forcing mechanisms that reward and empower reductions in CO_2 emissions, and/or CO_2 removal from the atmosphere. Such incentive mechanisms, some of which are already in place include the 45-Q tax credit [[25]] and other incentives made available via California's low-carbon fuel standard (LCFS) [[26]], as two prominent examples. These mechanisms, which offer incentives/credits up to $35 per ton (for CO_2 utilization, by 2027 [[25]]), up to $50 per ton (for CO_2 sequestration, or for EOR operations; by 2027 [[25]]), and up to $180 per ton (LCFS) [[26]] offer a means to substantially offset the cost of emplacing CO_2 abatement technologies. While this is unquestionably a step in the right direction; more is needed. For example, tax credits are valuable only if there is a tax-obligation to address. Thus, established corporations are disproportionately advantaged by tax credits, while new entrants, are less so. Simultaneously, while many CO_2 abatement pathways may result in the production of a (lower) carbon fuel; in other cases, other products may be produced. Thus, it is necessary to develop support structures and systems (i.e., subsidies, rebates, advantaged financing mechanisms, etc.) that incentivize CO_2 emissions mitigation by both early-stage innovators who seek to transform the heavy industry sector, and established (heavy industry) corporations. These types of progressive actions lie at the origin of the tremendous success of community (and grid-scale) solar power generation in the U.S. Thus, more expansive thinking, e.g., in terms of incentive mechanisms and the consequent market forces that they could unleash, is needed to support the creation, adoption and diffusion of new technologies and economic opportunities that may otherwise be unfeasible to exploit, but that are prerequisite to deploy CO_2 mitigation/net-zero technologies; rapidly, scalably and globally.

[24] Our World in Data. CO_2 emissions per capita vs GDP per capita https://ourworldindata.org/grapher/co-emissions-per-capita-vs-gdp-per-capita-international- (accessed Sep 12, 2019).
[25] Office of the Law Revision Council. 26 USC 45Q: Credit for carbon dioxide sequestration https://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim) (accessed Sep 12, 2019).
[26] California Air Resources Board. Low Carbon Fuel Standard Program https://www.arb.ca.gov/fuels/lcfs/lcfs.htm (accessed Sep 12, 2019).

Thank you again for the opportunity to testify on this important topic.