TURNING CARBON INTO GOLD: INCENTIVIZING THE NEW ALCHEMY

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ABSTRACT

One approach to help address climate change is carbon capture and utilization (CCU). CCU involves capturing atmospheric carbon dioxide and using it to generate marketable products. CCU, however, needs significant additional research and development to reach its potential. Development of CCU could yield benefits far in excess of its actual ability to sequester carbon. Research and development of CCU could stimulate improvements in carbon capture technologies, incentivize the capture and sequestration of carbon, and generate products that can benefit society generally. Nevertheless, most CCU uses remain only theoretical, or significant barriers prevent their current implementation.

A number of policy tools are available to incentivize CCU research: patents, prizes, grants, and tax credits. This article reviews the strengths and weaknesses of each. Then, it discusses how best to apply these policies to incentivize a number of possible CCU opportunities, including construction materials, fuels, chemicals, and algae-derived products.

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I. THE NEED TO DEVELOP CCU

Despite recent efforts to reduce carbon dioxide emissions, scientists still project that we will not avoid dangerous climate change. A means to reduce atmospheric carbon and accelerate carbon dioxide removal could be carbon utilization – using carbon in marketable goods. Despite promise in helping to reduce carbon dioxide, the process and products required for significant carbon utilization remain undeveloped.

A. Dangerous Climate Change Is Unavoidable

The parties to the 2015 Paris Agreement committed to hold the rise in warming to "well below 2.0°C."[1] The Paris Agreements and earlier global pacts targeted a rise of 2.0°C as the level to avoid because at that level "dangerous anthropogenic interference with the climate system" will be unavoidable.[2] Scientists consider warming at this level to be catastrophic for humans, plants, and animals.[3] Some of the expected consequences of warming at this level include rendering parts of the planet unlivable; increasing the number of heatwaves, floods, storms and droughts; and forcing migrations from coastal areas endangered by sea level rise.[4]

The parties to the Paris Agreement further agreed to attempt to hold the temperature rise to 1.5°C.[5] Recent analyses indicate that even warming to the 1.5°C level will cause serious regional consequences, such as extreme temperature warming, heavy precipitation, and droughts.[6] Furthermore, recent analysis concludes that the climate could reach tipping points with a rise of between only 1°C to 2°C.[7] Such

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1. Adoption of the Paris Agreement, UNFCC Conference of the Parties, 21st Sess., U.N. Doc. FCCC/CP/2015/10/Add.1 (Dec. 12, 2015), at art. 2(1)(a) (Paris Agreement) http://unfccc.int/files/home/application/pdf/paris_agreement.pdf.

2. Lena R. Boysen et al., *The Limits to Global-Warming Mitigation by Terrestrial Carbon Removal*, 5 EARTH'S FUTURE, MAY 17, 2017, 463, 463–474.

3. Laura Millan Lombrana, *Global Warming Forecast Improves Slightly after Biden's Pledge*, BLOOMBERG L. ENV'T & ENERGY REP. (May 4, 2021), available at https://perma.cc/UA8Q-8PU6.

4. *Id*.

5. *Id*.

6. Valérie Masson-Delmotte et al., GLOBAL WARMING OF 1.5°C 8 (2018).

7. Climate tipping points will occur when continued increases in atmospheric greenhouse gases result in major changes in Earth systems. Sybren Drijfhout et al., *Catalogue of Abrupt Shifts*

tipping points could include winter Arctic sea ice loss, abrupt Tibetan snow melt, permafrost collapse, and Amazon rainforest dieback, among several others.[8]

Unfortunately, temperature rises exceeding these levels are becoming increasingly likely. For instance, scientists estimate that the likelihood that the global temperature will exceed 1.5°C warming as soon as 2027 to be 40%.[9] Moreover, even exceeding the 2.0°C target is becoming likely. When considering current national policies, recent projections hold that by 2100 the global temperature rise will reach as high as 2.9°C.[10] Even when nonbinding national pledges and targets are factored into the calculation, warming still projects to reach 2.4°C.[11]

B. The Role of CCU in Responding to Climate Change

Carbon capture and utilization (CCU) can play a significant role in addressing climate change. While CCU is unlikely to reduce atmospheric carbon dioxide substantially, it can make a significant contribution. Maybe more importantly, it can provide additional benefits: encouraging development of carbon capture technology, incentivizing carbon dioxide removal installations, and helping offset emissions from sectors that are difficult to decarbonize. Scientists have identified a number of possible CCU applications, but they are largely undeveloped or presently too costly to implement at scale.

1. CCU's Role in Addressing Climate Change

Carbon capture and utilization attempts to use atmospheric carbon as a raw material. The National Academy of Sciences defines CCU as "the manufacture of valuable products from a gaseous carbon waste feedstock (carbon dioxide and methane) that results in a net

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in Intergovernmental Panel on Climate Change Climate Models, PNAS, E5777-E5786, E5777 (2015).

8. *Id*. at E5779.

9. World Meteorological Organization, *New Climate Predictions Increase Likelihood of Temporarily Reaching 1.5 °C in Next 5 Years* (May 27, 2021), available at https://public.wmo.int/en/media/press-release/new-climate-predictions-increase-likelihood-of-temporarily-reaching-15-%C2%B0c-next-5.

10. Claire Stockwell et al., WARMING PROJECTIONS GLOBAL 1 (2021).

11. *Id*.

reduction of greenhouse gases emitted to the atmosphere."[12] CCU would change the treatment of carbon dioxide from being only a pollutant to also a valuable raw material.[13]

CCU could contribute to addressing climate change in a number of ways. CCU could help achieve mitigation goals by capturing carbon dioxide from emissions sources that would otherwise be released into the atmosphere.[14] It could provide a substitute fuel to replace current fossil fuels.[15] CCU could contribute to goals for reducing carbon emissions.[16] It could also help to decarbonize certain sectors that otherwise would be difficult to decarbonize.[17] In addition, the development of new markets relating to CCU could accelerate the development of the carbon capture industry generally.[18] Finally, CCU could be important to keep the costs of addressing climate change from rising significantly higher.[19]

Current estimates project that CCU could significantly benefit both mitigation efforts and the economy. Estimates of the amount of carbon that CCU use could reach as high as 7 billion tons.[20] This constitutes 19% of current global carbon dioxide emissions, which exceed 36 Gt.[21] The market for these products is projected to reach

12. National Academies of Sciences (NAS), Engineering, and Medicine, GASEOUS CARBON WASTE STREAMS UTILIZATIONS: STATUS AND RESEARCH NEEDS 15 (2019).

13. F. R. Lucci et al., NEW CARBON ECONOMY CORPORATE ROUNDTABLE: CARBON CONVERSION TO VALUABLE PRODCUTS 4 (2019).

14. CO2 SCIENCES AND THE GLOBAL CO2 INITIATIVE (CO2 SCIENCES), GLOBAL ROADMAP FOR IMPLEMENTING CO2 UTLIZATION 10 (2016).

15. *Id*.

16. *Id*.

17. Jeffrey Bobeck et al., CARBON UTLIZATION – A VITAL AND EFFECTIVE PATHWAY FOR DECARBONIZATION (2019).

18. Jessica Strefler et al., TOWARDS NET ZERO — CARBON DIOXIDE REMOVAL AND UTILIZATION (2019). Such sectors include agriculture, aviation, food production, and marine transportation. Mark Workman et al., *An Assessment of Options for CO2 Removal from the Atmosphere*, ENERGY PROCEDIA 4 (2011) 2877–2884, 2877.

19. Bobeck, *supra* note 17, at 1. For instance, researchers anticipate that the costs of fully decarbonizing the electric sector increase sharply after the reduction of 90% of emissions without incorporating carbon sequestration. John E. T. Bistline & Geoffrey J. Blanford, *Impact of Carbon Dioxide Removal Technologies on Deep Decarbonization of the Electric Power Sector*, NATURE COMMUNICATIONS 9 (2021). Overall, studies consistently project that reducing emissions sufficiently to avoid a 2°C rise in temperatures could cost two to three times more without large scale carbon sequestration. Myles Allen et al., *Certificates for CCS at Reduced Public Cost: Securing the UK's Energy and Climate Future*, ENERGY BILL 2015 2 (2015).

20. *Id*. at 5.

21. *Global CO2 Emissions Have Been Flat for a Decade, New Data Reveals*, CARBONBRIEF (November 4, 2021), https://www.carbonbrief.org/global-co2-emissions-have-been-flat-for-a-decade-new-data-reveals.

$800 billion by 2030.[22]

2. CCU Opportunities

A key benefit of developing CCU is that it will help reduce the cost of carbon capture technologies. The high cost of carbon capture and sequestration (CCS) has slowed its deployment.[23] Concern over the high costs of CCS has raised interest in pursuing CCU.[24] Demand for carbon dioxide acquired through carbon capture could create market pull, which would lead to the scaling up of carbon capture technology and a concomitant reduction in its costs.[25] Scientists anticipate that increasing CCU will help to overcome current reluctance regarding CCS, including its cost and public acceptance.[26] Furthermore, utilization of the captured carbon might make carbon capture financially viable.[27]

3. Possible CCU Products

Scientists anticipate that carbon can provide the basis for numerous existing or novel products. Carbon is a relatively benign material that can be incorporated into a wide range of products.[28] However, it is also thermodynamically highly stable, so its conversion into such materials will be energy intensive.[29] As a result, a number of

22. NAS, *supra* note 12, at 21.

23. Ahmed Al-Mamoori et al., *Carbon Capture and Utilization Update*, ENERGY TECHNOL. 2017, 5, 1–17, 1. Analysis by the United Nations' Intergovernmental Panel on Climate Change has shown the importance of CCS. 101 out of 166 of its integrated assessment models (out of a total of 900) that showed a likelihood of keeping warming under 2°C by 2100 required some form of carbon dioxide removal to remain under this level of warming. Christopher B. Field & Katharine J. Mach, *Rightsizing Carbon Dioxide Removal*, 356 SCIENCE 706, 707 (2017).

24. The Royal Society, *supra* note 21, at 4.

25. David Roberts, *Pulling CO2 out of the Air and Using It Could Be a Trillion-Dollar Business*, VOX, Nov 22, 2019, available at https://www.vox.com/energy-and-environment/2019/9/4/20829431/climate-change-carbon-capture-utilization-sequestration-ccu-ccs.

26. Al-Mamoori, *supra* note 23, at 8.

27. Krysta Biniek et al., *Why Commercial Use Could Be the Future of Carbon Capture* (January 12, 2018), available at https://www.mckinsey.com/business-functions/sustainability/our-insights/why-commercial-use-could-be-the-future-of-carbon-capture.

28. Niall Mac Dowell et al., *The Role of CO2 Capture and Utilization in Mitigating Climate Change*, NATURE CLIMATE CHANGE, Vol. 7, 243–49, 244 (Apr. 2017).

29. Rosa M. Cuéllar-Franca & Adisa Azapagic, *Carbon Capture, Storage and Utilisation*

issues require addressing before CCU can reach its potential.

Carbon dioxide fixation in products will vary substantially.[30] The first systematic review of potential CCU opportunities concluded that the usage and lifetime of CCU products falls into three categories. First, inclusion in synthetic fuels provides short-term storage. Second, usage in plastics or polymers would provide medium-term storage. Finally, inclusion in building materials would provide long-term storage.[31] Thus, when evaluating CCU options and their incentivization, policymakers must identify both the amount of carbon that they will fix and the period over which the carbon will be removed from the atmosphere.[32] A shorter period of fixation is not necessarily disqualifying, but it necessitates that the products' use be repeated very often.[33]

Researchers have identified ten different CO_2 utilization pathways.[34] They organize these specific pathways into three categories, two of which are relevant here.[35] First, "cycling" pathways include those utilization techniques that pass carbon through industrial systems in brief timescales, such as days, weeks, or months. Prominent in this group are CO_2-based fuels and chemicals.[36] Alternatively, "closed" pathways store carbon nearly permanently. Included among

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Technologies: A Critical Analysis and Comparison of Their Life Cycle Environmental Impacts, J. CO2 UTILIZATION 9 (2015) 82–102, 86.

30. Peter Markewitz et al., *Worldwide Innovations in the Development of Carbon Capture Technologies and the Utilization of CO2*, ENERGY ENV'T SCI. (2012), 5, 7281–7305, 7282–83.

31. Strefler et al., *supra* note 18, at 10. Conversely, scientists project that CCS will provide nearly permanent sequestration of carbon, trapping it for centuries. Juan Alcalde et al., *Estimating Geological CO2 Storage Security to Deliver On Climate Mitigation*, NATURE COMMC'N 1 (2018).

32. Strefler et al., *supra* note 18, at 10.

33. Markewitz et al., *supra* note 30, at 7283.

34. Cameron Hepburn et al., *The Technological And Economic Prospects For CO2 Utilization And Removal*, NATURE, Vol 575, 7 November 2019, 87–97, 87. This analysis identifies the following ten pathways:

> (1) CO2-based chemical products, including polymers; (2) CO2-based fuels; (3) microalgae fuels and other microalgae products; (4) concrete building materials; (5) CO2 enhanced oil recovery (CO2-EOR); (6) bioenergy with carbon capture and storage (BECCS); (7) enhanced weathering; (8) forestry techniques, including afforestation/reforestation, forest management and wood products; (9) land management via soil carbon sequestration techniques; and (10) biochar. *Id*.

35. The third category includes "open" pathways, which typically involve biological systems that can remove and store substantial quantities of carbon in "leaky" natural systems that could experience large-scale flux of carbon back into the atmosphere. *Id*. at 87–88.

36. *Id*. at 87. The source of the carbon will impact the sequestration effect of CCU fuels. Synthentic fuels that reuse carbon of fossil origin can at best halve emissions; carbon captured from the atmosphere can close the carbon cycle and become carbon neutral. Strefler et al., *supra* note 18, at 10.

these pathways are enhanced oil recovery,[37] enhanced weathering,[38] and inclusion in the built environment.[39] Both open and closed pathways may be economically viable without substantial shifts in prices.[40] Eventually, all pathways need to become closed to achieve net zero emissions. To become closed, the CO_2 will need to be sourced from the atmosphere, through some form of carbon capture.[41]

Another analysis of CCU opportunities identified six markets or product clusters. It categorized these clusters by the number of active developers, technology pathways, and end products. These categories are algae (as a biofuel or food product), building materials (conversion to carbonates or infusion into materials), chemical intermediates (methanol and syngas), fuels (methane production), novel materials (carbon fibers), and polymers (polycarbonates).[42]

The following discussion surveys several of the more promising applications of CCU. It addresses their potential, both in carbon sequestration and economic return.

a. Building Materials

A number of common materials in this category include cement, concrete, paving asphalt, and aggregates.[43] Their total market value is

37. Enhanced oil recovery involves injection of a substance, often CO2, into a reservoir to repressurize and release any oil or gas that may be trapped in the formation. The injected CO2 releases the oil or gas, which becomes combined with the CO2 and can then be pumped out. The CO2 can be separated and re-injected to repeat the process. Al-Mamoori, *supra* note 23, at 8. Currently, enhanced CO2 oil recovery accounts for approximately 4 to 15% of additional oil production. National Energy Technology Laboratory, CARBON DIOXIDE ENCHANCED OIL RECOVERY 14 (2010). Technological improvements, however, could increase the amount of recovered oil to 22% or even as high as 60%. *Id*.

38. Atmospheric CO2 naturally forms a chemical bond with reactive minerals. NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE, NEGATIVE EMISSIONS TECH. AND RELIABLE SEQUESTRATION: A RES. AGENDA 39 (2019). Enhanced weathering augments this natural weathering process. It involves mining and grinding particular minerals to small grain sizes to increase their surface area exposed for weathering. Jessica Strefler et al., *Potential and Costs of Carbon Dioxide Removal by Enhanced Weathering of Rocks*, 13 ENV'T RES. LETTERS 1, 1 (2018).

39. Hepburn et al., *supra* note 34, at 87. This is discussed more fully in the next section.

40. *Id*. at 95.

41. *Id*. at 90.

42. CO2 Sciences, *supra* note 14, at 12.

43. Rory Jacobson & Matt Lucas, A REVIEW OF GLOBAL AND U.S. TOTAL AVAILABLE MARKETS FOR CARBONTECH 4 (undated).

approximately $100 billion domestically and $1.4 trillion globally.[44] The manufacturing of construction materials generates 11% of CO_2 emissions.[45] Indeed, if the cement industry were a separate country, it would rank third among CO_2 emitters behind only China and the United States.[46]

Concrete is the most used human-made material.[47] Importantly, concrete use is measured in gigatons, the same unit used to measure annual CO_2 emissions.[48] Thus, unlike other potential CCU products, concrete is used at a scale commensurate to the magnitude at which society releases CO_2 into the atmosphere. Accordingly, CCU concrete could make a significant contribution to carbon reduction.

Concrete is a blend of several materials, including cement, water, and aggregates.[49] When water activates cement, it binds the aggregates into a rigid mix.[50] Cement has a substantial carbon footprint.[51] Cement manufacturing alone is responsible for 2 gigatons of CO_2[52] and 5.6% of global CO_2 emissions.[53] The manufacturing process releases CO_2 through energy use and calcination reactions.[54]

Replacing water with CO_2 during the mixing process enhances the strength of concrete, allowing for the use of less cement. This reduces the carbon intensity of concrete.[55] Such "carbon curing" can produce

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44. *Id*.

45. Jay H. Arehart et al., *On the Theoretical Carbon Storage and Carbon Sequestration Potential of Hempcrete*, J. CLEANER PROD. 266 (2020) 121846, 1.

46. Stephen Lee, *Concrete Still a Barrier to Climate-Friendly Infrastructure Plan*, BLOOMBERG LAW ENVIROMENT & ENERGY REPORT NEWSLETTER (May 25, 2021), available at https://perma.cc/5J4A-KTYQ.

47. Jacob Schneider, *Decarbonizing Construction through Carbonation*, PNAS (June 9, 2020), vol. 117, no. 23, 12515–17, 12517.

48. *Id*.

49. David Roberts, *These Uses of CO2 Could Cut Emissions — and Make Trillions of Dollars* (*These Uses*), VOX, Nov 27, 2019, available at https://www.vox.com/energy-and-environment/2019/11/13/20839531/climate-change-industry-co2-carbon-capture-utilization-storage-ccu.

50. *Id*.

51. Julia Rosen, *Turning Carbon into Concrete Could Win UCLA Team a Climate Victory — and $7.5 Million*, LOS ANGELES TIMES (January 16, 2020), available at https://www.latimes.com/environment/story/2020-01-16/ucla-xprize-team-turning-carbon-into-concrete.

52. Ajay Gambhira et al., *Energy System Changes in 1.5°C, Well Below 2°C and 2°C Scenarios*, ENERGY STRATEGY REVIEWS 23 (2019) 69–80, 78.

53. Jeffrey Rissman, CEMENT'S ROLE IN A CARBON-NEUTRAL FUTURE 1 (2018).

54. *Id*. at 2.

55. Rissman, *supra* note 53, at 11. Cement is the primary contributor to the CO2 content of concrete. The contribution of other ingredients is essentially "the noise" compared to the share added by cement. Schneider, *supra* note 47, at 12516.

concrete that is 4% CO_2.[56] Benefits of curing include shortening curing times, increasing concrete's water resistance, and strengthening the concrete.[57] Using CO_2 in the cement-making process is an example of an essentially closed pathway since it could possibly store the carbon for a century or longer.[58]

Cement already naturally sequesters some carbon through the process of mineral carbonation. Mineral carbonation is a chemical process in which CO_2 reacts with a metal oxide to form carbonates.[59] The process converts an organic, stable material, CO_2, into an inorganic, even more stable material, a carbonate.[60] Specifically, CO_2 can be added in the production of cement and aggregate to form carbonates.[61] Manufacturers use carbonates to produce construction materials, such as concrete.[62] These relatively stable carbonates, importantly, can sequester CO_2 for decades or centuries without risk of leakage.[63] Analyses have concluded that mineral carbonation could reduce the global warming potential of the CO_2 used for the process from 4 to 48% when compared to its global warming impact without capture.[64] However, this technology is not ready for large-scale implementation, and its costs are still too high.[65] Furthermore, testing and validation of new materials is also necessary.[66]

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56. Biniek, *supra* note 27. CarbonCure Technologies, a Nova Scotia company, has begun injecting liquid CO2 during the concrete mixing process. The process can reduce concrete's carbon content by 5-7%. Jane Margolies, *Concrete, a Centuries-Old Material, Gets a New Recipe*, THE NEW YORK TIMES (August 11, 2020), available at https://www.nytimes.com/2020/08/11/business/concrete-cement-manufacturing-green-emissions.html?action=click&module=Editors%20Picks&pgtype=Homepage.

57. Biniek, *supra* note 27.

58. Roberts, *These Uses*, *supra* note 49.

59. Cuéllar-Franca & Azapagic, *supra* note 29, at 86.

60. NAS, *supra* note 12, at 21.

61. Bobeck, *supra* note 17, at 9.

62. NAS, *supra* note 12, at 21.

63. Cuéllar-Franca & Azapagic, *supra* note 29, at 87. By contrast, scientists recognize that underground storage of CO2 will inevitably result in a certain amount of leakage. Estimating over a 10,000 year period, they project that from 2% to 6% of the injected CO2 will leak from regulated storage, but as much as 22% to 33% of CO2 will leak from unregulated storage. Alcalde, *supra* note 31, at 9.

64. Cuéllar-Franca & Azapagic, *supra* note 29, at 92. The wide range in the estimates resulted because the three calculations that provide the basis for the analysis relied upon different methods for the carbonation. *Id*.

65. *Id*. at 87. Low-carbon gravel aggregate currently would sell for $70-100 per ton, whereas typical aggregate can sell for as low as $50 per ton. Bobeck, *supra* note 17, at 11.

66. NAS, *supra* note 12, at 21–23. New or developing technologies may provide additional means to utilize CO2 in the manufacture of construction materials. The company CO2 Concrete, LLC, for instance, has developed a process to replace cement with binding agents that absorb and

Thus, building materials satisfy the most important requirements for effective CCU development – use at the scale of billions of tons and long-term sequestration.[67] Moreover, among CCU opportunities, they have the greatest potential for utilizing large quantities of CO_2 in the near term.[68] Total global emissions reductions potential from construction materials could reach as high as 1 billion to 10 billion tons by 2030.[69] Furthermore, analysts project the demand for concrete to skyrocket during this century as population shifts stimulate the building of cities.[70]

b. Synthetic Fuels

Technically, manufacturers can convert carbon dioxide into any type of fuel derived from petroleum.[71] Already, manufacturers produce a number of synthetic fuels. These are liquid fuels that producers derive from coal, natural gas, and biomass feedstocks through chemical conversion processes.[72] Similarly, treating CO_2 with a reducing agent can yield many fuels, including methane, methanol, and formic acid.[73]

Importantly, utilization of CO_2 to produce synthetic fuels will not sequester carbon for long periods;[74] instead, their chief benefit results from replacing traditional fuels with low-carbon fuels.[75] Use of synthetic fuels can be especially critical to reduce emissions from

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mineralize CO2. Roberts, *These Uses*, *supra* note 49. The enterprise Low Emissions Intensity Lime & Cement is developing a process that seeks to produce a purified CO2 stream from the production process for cement and lime which can then be sequestered or reused. *Id*.

67. NAS, *supra* note 12, at 219.

68. *Id*.

69. Bobeck, *supra* note 17, at 9.

70. Rosen, *supra* note 51. Specifically, projections estimate that global urbanization and population growth will require the construction of 230 billion m3 of new buildings by 2060. Francesco Pomponi et al., *Buildings as a Global Carbon Sink? A Reality Check on Feasibility Limits*, ONE EARTH 3, 157–61, 157 (August 21, 2020). For an example of the potential impact these structures could have, if builders used CCU processes in the construction of the Salesforce Tower in San Francisco, which required nearly 100,000 yd3 of concrete, that single building structure could have reduced atmospheric carbon by more than 100.5 million pounds of CO2. Schneider, *supra* note 47, at 12517.

71. Biniek, *supra* note 27.

72. The Royal Society, *supra* note 21, at 7.

73. Samaresh Chandra Sau et al., *Transforming Atmospheric CO2 into Alternative Fuels: a Metal-Free Approach under Ambient Conditions*, CHEM. SCI. (2019) 10, 1879 –84, 1879.

74. Mac Dowell et al., *supra* note 28, at 247 (noting that CO2 conversion to methanol will not store CO2 for a significant period).

75. The Royal Society, *supra* note 21, at 15.

otherwise hard to decarbonize sectors, such as aviation and marine transportation.[76] The development of low-carbon fuels would be particularly helpful because they provide a means to reduce emissions in these sectors while operating within the current infrastructure.[77]

Scientists consider the conversion of CO_2 into synthetic fuels to be the most promising CCU pathway.[78] Nevertheless, projections of its ultimate impact varies dramatically. For instance, projected CO_2 utilization in fuels range from 1 to 4.2 $GtCO_2$ per year.[79] The domestic and global markets for these fuels can reach $900 billion and $3.8 trillion, respectively.[80]

Despite the promise of this pathway, several hurdles remain. Besides advances in chemistry, development of these fuels will necessitate advances in process and reaction engineering and in novel process design.[81] In addition, the costs of conversion of CO_2 into synthetic fuels remains high, necessitating policy support.[82] Furthermore, because of the high capital costs involved in fuel development and processing, this pathway (and algae, *infra* at Section I.B.3.e.) will benefit from economies of scale and learning by doing, which inevitably result from increased production.[83]

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76. *Id*. at 16. The chemical conversion of CO2 to synthetic fuels will require energy, which will need to be low carbon or renewable to achieve decarbonization through the substitution of the fuels. *Id*. at 14.

77. Hepburn et al., *supra* note 34, at 91.

78. Al-Mamoori, *supra* note 23, at 9. Projections estimate that derived fuels may have both a larger market potential and larger emission reduction effect than many other possible uses, such as chemicals and polymers. Bobeck, *supra* note 17, at 11. Low-carbon fuel mandates will help drive this potential. CO2 Sciences, *supra* note 14, at 15. California's low-carbon fuel standard (LCFS) regulates a fuel's "life-cycle" emissions. These include CO2 emissions resulting from fuel production, including extracting and refining the fuel, as well as emissions related to the finished fuel's transportation to market. James W. Coleman, *Importing Energy, Exporting Regulation*, 83 FORDHAM L. REV. 1357, 1369, n.71 (2014). Alternatively, five states (Louisiana, Minnesota, Missouri, Pennsylvania, and Washington) have enacted alternative fuel standards (AFS), which require that a specific percentage of fuels derive from alternative fuels, such as cellulosic and noncellulosic ethanol and biodiesel. Center for Climate and Energy Solutions, *Low Carbon and Alternative Fuel Standard*, last visited February 26, 2021, available at https://www.c2es.org/document/low-carbon-fuel-standard/. Oregon has enacted both an LCFS and an AFS. *Id*.

79. Hepburn et al., *supra* note 34, at 91.

80. Jacobson & Lucas, *supra* note 43, at 4.

81. The Royal Society, *supra* note 21, at 14.

82. Bobeck, *supra* note 17, at 11.

83. Hepburn et al., *supra* note 34, at 91. "Economies of scale" result as production costs per unit of output fall as fixed costs get spread over an increasing volume of production. Rising production volumes also enable efficiencies through greater divisions of labor. Saed Alizamir et al., *Efficient Feed-In-Tariff Policies for Renewable*, 64 OPERATIONS RES. 52, 53 (2016). "Learning by doing" refers to a concept recognized in economics that costs decline as production increases

c. *Chemicals and Other Manufactured Products*

Another sector that might utilize captured CO_2 is the chemical industry. Manufacturers already use CO_2 to develop chemicals and plastics.[84] They can also use CO_2 to produce a range of chemical intermediates (feedstocks for industrial processes) and polymers (precursors for plastics, adhesives, and pharmaceuticals).[85] However, as with fuels, utilization in chemicals stores CO_2 only until the chemical is used, though storage in polymers can last for several decades.[86] Moreover, for CCU purposes, the domestic chemical market is minimal when compared to other CCU options.[87] While the market for plastics may be potentially substantial, derived polymers are expensive and will require additional research and policy support.[88]

d. *Algae*

Another area for CO_2 use involves algae. Algae can convert sunlight and CO_2 into marketable products, including chemicals, foods, and fuels.[89] A number of potential algae products may arise in the near term, including biofertilizers and aquaculture.[90] Algae-derived protein also can provide dietary protein for both humans and animals.[91] Other possible uses – as biofuels or bioplastics, for instance – still require additional research and development to determine viability at scale and to reduce costs.[92]

Unlike using CO_2 to produce chemicals[93] or to provide food

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because manufacturers learn how to produce the item more efficiently. *Id*.

84. Biniek, *supra* note 27.

85. Roberts, *These Uses*, *supra* note 49.

86. Mac Dowell, *supra* note 28, at 246.

87. Jacobson & Lucas, *supra* note 43, at 4. Even at a global level, this market is only $20 billion. *Id*. At least one study projects that use of CO2 in the chemical industry could eventually use up to 3.7 GtCO2 (approximately 10 percent of current emissions). Arne Kätelhön et al., *Climate Change Mitigation Potential of Carbon Capture and Utilization in the Chemical Industry*, PNAS (June 4, 2019), vol. 116, no. 23, 11187–94, 11188. However, this projection relies upon the further development of particular technologies which will still require "substantial research and development efforts and novel production facilities." *Id*.

88. Roberts, *These Uses*, *supra* note 49.

89. NAS, *supra* note 12, at 97.

90. Bobeck, *supra* note 17, at vi.

91. NAS, *supra* note 12, at 100.

92. Bobeck, *supra* note 17, at vi.

93. Markewitz et al., *supra* note 30, at 7282.

products,[94] an advantage of using it to support algae growth is that this does not require high-purity CO_2.[95] Unfortunately, all current and prospective technologies for conversion of CO_2 by algae into fuels or other products face technical challenges and limitations.[96] Among others, photosynethesis is especially inefficient at converting solar energy into proteins, and capital and operations costs are higher than for comparable sources.[97] Finally, generating fuels, bioplastics, and other products from algae require additional research to lower costs and attain commercial viability.[98]

e. Other Uses

Scientists have identified a number of other possible uses for captured carbon. The food and drink industries already use CO_2 as a carbonating agent, a preservative, a packaging gas, and as a solvent for flavor extraction and decaffeination.[99] In the metal industry, manufacturers use CO_2 for a number of uses, including chilling parts for shrink fitting, hardening of moulds, and contributing to oxygen furnace processes.[100] Other industries that use CO_2 include pulp and paper processing, water treatment, and printed circuit board manufacturing.[101]

The energy industry also could use CO_2 in a number of ways. In conventional generation, CO_2 can replace steam in turbines to enable generators to run more efficiently.[102] CO_2 requires less energy to

94. Cuéllar-Franca & Azapagic, *supra* note 29, at 86.

95. Bobeck, *supra* note 17, at 14. This assumes that the algae is grown in ponds, which do not require high-purity CO2, but do require substantial areas of land. Cuéllar-Franca & Azapagic, *supra* note 29, at 87. Alternatively, photo-bioreactors require less space, but do necessitate the use of a purified CO2 stream. Al-Mamoori, Krishnamurthy, Rownaghi, & Rezaei, *supra* note 23, at 10.

96. NAS, *supra* note 12, at 121.

97. *Id*. at 98.

98. Bobeck, *supra* note 17, at 14.

99. Cuéllar-Franca & Azapagic, *supra* note 29, at 86. One company currently hydrogenates CO2 into pure ethanol, from which it produces "Green Vodka." Geoffrey Ozin, *Flying High on Carbon Dioxide: Decarbonizing Aviation*, ADVANCED SCIENCE NEWS (Jun 4, 2020), available at https://www.advancedsciencenews.com/flying-high-on-carbon-dioxide-decarbonizing-aviation/. A problem with using CO2 in food-related processes is that those uses typically require the CO2 streams to achieve purity levels of 99% or greater. Tryfonas Pieri et al., *Holistic Assessment of Carbon Capture and Utilization Value Chains*, ENVIROMENTS 6 (2018).

100. *Id*.

101. *Id*.

102. Biniek, *supra* note 27.

compress than steam does. Its use can thus increase the energy-conversion rate from approximately 33% to as high as 49%.[103] Finally, the energy sector could also use renewable energy to covert CO_2 into low-carbon fuels.[104] This could have two results. First, this could constitute a form of long-term energy storage – fuel converted in the summer using solar and wind power could provide energy in winter months.[105] Second, by increasing the effective capacity of wind and solar, such storage capabilities could increase the installation of renewable energy sources.[106]

4. Obstacles to Scaling Up CCU

Despite their possibilities, CCU technologies are not yet ready to achieve their sequestration potential. Current projections estimate that CCU can sequester approximately 10% of annual global CO_2 emissions (a reduction of 3.6 gigatons of CO_2) within the next several decades.[107] However, to achieve this target, we need to implement CCU technologies at scale, which will require technological development and supportive regulatory and market conditions.[108] Even under the best of circumstances, CCU will sequester only a fraction of the CO_2 that CCS could remove from the atmosphere.[109]

All potential CCU sectors must overcome obstacles before they are ready to provide products for commercial markets. Depending upon the sector, remaining obstacles involve technology, cost, or

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103. *Id*. The energy-conversion ratio refers to the amount of energy in fuel that is converted into electricity. *Id*.

104. Jon Gertner, *The Tiny Swiss Company That Thinks It Can Help Stop Climate Change*, THE NEW YORK TIMES (Feb. 12, 2019).

105. *Id*. Importantly, these fuels could provide both lower-cost and longer-life storage than is possible with batteries. *Id*.

106. Oleksandr S. Bushuyev et al., *What Should We Make with CO2 and How Can We Make It?*, JOULE 2, 1–8, 2 (May 16, 2018). A related approach would be to use captured carbon to produce "blue," or "decarbonized," hydrogen from natural gas. Sonja van Renssen, The Hydrogen Solution?, NATURE CLIMATE CHANGE, Vol. 10 (September 2020) 799–801, 800.

107. NAS, *supra* note 12, at 3.

108. *Id*. Furthermore, the source of the CO2 matters. Using more concentrated sources, such as directly from an emissions source as opposed to from the ambient air, can increase the global warming potential effect of CCU by 30-60%. Cuéllar-Franca & Azapagic, *supra* note 29, at 97. The difference arises because the concentration of CO2 in the ambient air is 100 to 300 times lower than in the emissions from a gas- or coal-fired power plant. National Research Council (NRC), CLIMATE INTERVENTION: CARBON DIOXIDE REMOVAL AND RELIABLE SEQUESTRATION 68 (2015).

109. The Royal Society, *supra* note 21, at 5.

market acceptance.[110] For instance, a fundamental need is the development of catalysts that enable CO_2 to be used to generate products at the scale of megatons.[111] Advancement is also necessary in process systems.[112] Furthermore, the identification, development, and implementation of value chains between CO_2 sources and utilizers will require the study of each stage of the chain and assessment of the entire system as a whole.[113]

Moreover, research is still required on a number of aspects of CCU. For instance, fundamental research still needs to be conducted concerning issues directly or indirectly related to the scaling up of CCU. Such areas include the fundamental understanding of catalysis, the inexpensive production of green hydrogen, and further reduction of the costs of renewable energy to support the conversion of carbon dioxide into usable products.[114]

Further research is also necessary to create the conditions conducive to attracting businesses to enter into these new markets.[115] Businesses typically do not invest in new products and markets when fundamental scientific knowledge has not been developed.[116] Accordingly, because many businesses are still waiting for significant uncertainties to be resolved, they have not begun investing in early stage CCU research and development.[117]

II. INCENTIVIZING RESEARCH

In view of the need for additional R&D on so many aspects of CCU, appropriate incentive structures need to be developed to accelerate related research and innovation. Typically, the government

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110. Bobeck, *supra* note 17, at vi.

111. The Royal Society, *supra* note 21, at 13. Since CO2 is relatively stable, *supra* note 29 and accompanying text, nearly all applications of CO2 require catalysts to generate the necessary reactions. The Royal Society, *supra* note 21, at 12. Presently, only a limited number of catalyst families exist for these processes. *Id*. at 13.

112. NAS, *supra* note 12, at 215. These include such processes as transporting mass scales of carbon gases, integrating carbon utilization with carbon capture technologies, and managing and recycling inputs. *Id*.

113. Pieri, *supra* note 99, at 11.

114. The Royal Society, *supra* note 21, at 3.

115. Lucci, *supra* note 13, at 6.

116. *Id* at 10.

117. *Id* at 12. Policy support will also facilitate the securing of financing for related projects. S.J. Friedmann et al., CAPTURING INVESTMENT: POLICY DESIGN TO FINANCE CCUS PROJECTS IN THE U.S. POWER SECTOR 6 (2020).

needs to intervene to ensure that the level of private investment in R&D reaches the necessary level.[118] Economists generally accept that underinvestment in R&D occurs in the absence of government encouragement.[119] Of course, increasing R&D is correlated with enhanced levels of innovation.[120] Government intervention can often be necessary to compensate for market conditions that lead private entities to under-invest in particular areas.[121] Government incentives can take one of two forms – rewards for innovators' efforts or reductions in their costs.[122] Implementation of such policies is critical since the gap between investment and availability of commercial processes and products is substantial.[123]

To encourage research and innovation in a particular field, the government has historically turned to four mechanisms: patents, prizes, grants, and tax credits. While these four policies have histories of successfully incentivizing innovation through different paths, none is superior in all contexts, and each has strengths that render it optimal in particular circumstances.[124] In this section, this paper will review each. In the following section, it will consider how these four approaches might best be used to encourage the development of CCU.

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118. Benjamin N. Roin, *Intellectual Property Versus Prizes: Refraining the Debate*, 81 U. CHI. L. REV. 999, 1020 (2014).

119. Noam Noked, *Integrated Tax Policy Approach to Designing Research & Development Tax Benefits*, 34 VA. TAX REV. 109, 114 (2014). Businesses do not invest sufficiently in R&D because they do not usually capture the full value of their investments. *Id*. This is because R&D investments tend to generate positive externalities in the form of knowledge "spill overs" to other parties. The inability of investors to prevent these spillovers and to receive the full benefit of their investments discourages them from investing more fully into R&D. Michael J. Graetz & Rachael Doud, *Technological Innovation, International Competition, and the Challenges of International Income Taxation*, 113 COLUM. L. REV. 347, 349 (2013).

120. Jay Shambaugh et al., ELEVEN FACTS ABOUT INNOVATION AND PATENTS 3 (2017) (noting that R&D investments correlate with increased generation of high-quality patent submissions).

121. Gary Guenther, PATENT BOXES: A PRIMER i (May 1, 2017).

122. Daniel J. Hemel & Lisa Larrimore Ouellette, *Beyond the Patents–Prizes Debate*, 92 TEX. LAW REV. 303, 311 (2013).

123. Shambaugh, *supra* note 120, at 8.

124. Hemel & Ouellette, *supra* note 122, at 309.

A. *Patents*

1. Patent Basics

At its essence, the patent system promotes two objectives: incentivizing research and development, and enabling the diffusion of inventions.[125] Historically, the patent system has substantially influenced the rate and direction of research and innovation.[126] The United States awards patents to inventions that are new and useful and are not obvious from prior patented inventions.[127] The United States Patent and Trademark Office (USPTO) grants patents for a 20-–year period.[128] The patent term applies a one-size-fits-all standard – regardless of the nature of the invention, the patent lasts for only 20 years,[129] though its effective life may be shorter.[130]

Patents include a right to exclude others from the use of their patented invention or process.[131] In exchange for their right to exclusive use, the patent law requires patentholders to disclose their inventions and the procedures for their use.[132] Disclosure is the "quid pro quo" of patentholders' right to exclude others from their

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125. Kristina M. L. Acrinée Lybecker, *How to Promote Innovation: The Economics of Incentives* IPWATCHDOG.COM (July 21, 2014), available at https://www.ipwatchdog.com/2014/07/21/promote-innovation-the-economics-of-incentives/id=50428/.

126. B. Zorina Khan, *Inventing Prizes: A Historical Perspective on Innovation Awards and Technology Policy*, BUSINESS HISTORY REV. 89 (Winter 2015): 631–660, 648. Notably, patents are a central feature of the innovation policy of the United States, the global industrial leader. *Id.* at 650.

127. Timothy J. Brennan et al., PRIZES OR PATENTS FOR TECHNOLOGY PROCUREMENT: AN ASSESSMENT AND ANALYTICAL FRAMEWORK 17 (2011).

128. Hemel & Ouellette, *supra* note 122, at 319–20. Once granted by the USPTO, a patent is presumptively valid, and parties contesting its validity must satisfy a clear and convincing standard. Michael J. Burstein & Fiona E. Murray, *Innovation Prizes in Practice and Theory*, 29 HARV. J.L. & TECH. 401, 451 (2016).

129. Lucas S. Osborn et al., *A Case for Weakening Patent Rights*, 89 ST. JOHN'S L. REV. 1185, 1240 (2015).

130. Matthew S. Clancy & GianCarlo Moschini, *Incentives for Innovation: Patents, Prizes, and Research Contracts*, APPLIED ECONOMIC PERSPECTIVES AND POLICY (2013) volume 35, number 2, 206-241, 209, doi:10.1093 / aepp / ppt012. The patent term is 20 years as calculated from the date of filing. The USPTO, however, requires on average three years before it approves the application. Consequently, the effective life of a patent averages 17 years. Osborn, Pearce, & Haselhuhn, *supra* note 129, at 1240–41.

131. Clancy & Moschini, *supra* note 130, at 208.

132. Irwin I. Park, *Extinguishing Exclusive Marketing Rights: Interpreting the Medical Innovation Prize Fund Act of 2011*, 22 DEPAUL J. ART, TECH. & INTELL. PROP L. 183, 187 (2011).

invention.[133] Dissemination of patentable advancements is a key aspect of the patent system.[134] It enables other inventors to build upon patented knowledge to develop their own innovations.[135] In fact, disclosure distinguishes the patent system from the other incentive schemes.[136]

While patents have played a significant role in the development of technologies generally,[137] they have been especially effective in stimulating innovation in particular industries.[138] The incentivizing effects of patents has varied by sector.[139] As relevant here, the sectors with the highest amount of patenting activity include chemicals and machinery.[140] Specifically, chemicals account for one-quarter of all patent applications, and mechanical engineering accounts for one-fifth.[141]

2. Patent Benefits

Patents provide two particular benefits: they compensate innovators for their work, and they utilize markets to determine the amount of compensation. As discussed above, the patent system provides innovators with the right to exclude others from using their inventions.[142] Of course, inventors then have the option of employing the inventions themselves or licensing them to interested parties.[143] Inventors, effectively, receive monopolies to use their inventions themselves or to license their use to others.[144] This temporary

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133. W. N. Price II, *Making Do in Making Drugs: Innovation Policy and Pharmaceutical Manufacturing*, 55 B.C. L. REV. 491, 524 (2014).

134. Heidi Williams, *Incentives, Prizes, and Innovation* 7 (14 November 2010) (unpublished).

135. Price II, *supra* note 133, at 524.

136. Hemel & Ouellette, *supra* note 122, at 355–56.

137. Khan, *supra* note 126, at 648.

138. Lybecker, *supra* note 125.

139. Clancy & Moschini, *supra* note 130, at 214.

140. Annette Alstadsæter et al., *Patent Boxes Design, Patents Location, and Local R&D*, ECONIMIC POLICY, Volume 33, Issue 93, January 2018, 131–177, 139 https://doi.org/10.1093/epolic/eix021.

141. *Id*. at 146.

142. Osborn, *supra* note 129, at 1240.

143. Hemel & Ouellette, *supra* note 122, at 320.

144. Park, *supra* note 132, at 186. As one commentator points out, the monopoly is not absolute – patent holders cannot block previous or new inventions. Daniel F. Spulber, *Prices Versus Prizes: Patents, Public Policy, and the Market for Inventions*, Northwestern Law & Econ

monopoly allows inventors to charge higher rates for the innovation,[145] which enables them to recover their development costs or more, if the invention is successful.[146] Such monopoly rights provide powerful incentives to researchers to innovate and disclose or market their inventions.[147]

An aspect of the patent system that sets it apart from other incentive schemes is its source of compensation for innovators. Whereas other methods (prizes, tax credits, and grants) require the government (ultimately, taxpayers) or private parties to fund the incentive system,[148] the patent system relies upon the actual customers of the inventions to reward the inventors. The system empowers patent holders to use monopoly pricing to raise the price to the eventual consumer.[149] In effect, patent licensing works akin to a sales tax.[150] Since inventors' compensation derives either from the willingness of consumers to pay more for the invention (or goods it can produce) or of other innovators to pay for licenses, inventors' rewards are effectively determined by the market for their inventions.[151] Not only does monopoly pricing assure a more accurate value for inventors' efforts, it also shifts the burden of the award to the actual consumers of the invention.[152] Relying upon the market to determine the value of an invention is particularly appropriate where an invention is difficult to value *ex ante* or by parties other than the inventors themselves.[153]

The dissemination mandate of the patent system provides additional benefits. First, it assures that the advancement in knowledge will be available to other potential innovators.[154] Second, it fosters efficiency since other innovators will not need to duplicate the

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Research Paper No. 14–15 11 (2014).

145. Price II, *supra* note 133, at 524.

146. Burstein & Murray, *supra* note 128, at 410. By relying upon the markets to compensate inventors, patents differ from most other incentive mechanisms because the value of the incentive is determined after the invention. Spulber, *supra* note 144, at 34. On the other hand, this does allow the awards to innovators to increase if, over time, society increases its valuation of their inventions. *Id*.

147. Gregory N. Mandel, *Innovation Rewards: Towards Solving the Twin Market Failures of Public Goods* (*Innovation Rewards*), 18 VAND. J. ENT. & TECH. L. 303, 308 (2016).

148. Hemel & Ouellette, *supra* note 122, at 348.

149. Jonathan H. Adler, *Eyes on a Climate Prize: Rewarding Energy Innovation to Achieve Climate Stabilization*, 35 HARV. ENV'T. L. REV. 1, 13 (2011).

150. Hemel & Ouellette, *supra* note 122, at 312.

151. *Id*. at 308.

152. *Id*. at 303.

153. Clancy & Moschini, *supra* note 130, at 226.

154. *Id*. at 211.

original work.[155] Finally, awareness of the successful innovation may encourage other inventors to focus their efforts in this area.[156]

Historical analysis of patents also finds that they are more likely than other incentive mechanisms, such as prizes, to yield high-value inventions.[157] High-value inventions or patents are those that can be commercialized; are upstream, parent patents that give rise to downstream, offspring patents; and are forward-cited.[158] Thus, they are high value because they lead to additional innovations and inventions.

Finally, the patent system also benefits from low administrative costs. As previously discussed, the system shifts the burden of payment of the innovator's reward to the consumer.[159] Moreover, the portion of administrative costs borne by the government is also relatively small. In large part, the administrative and enforcement costs of the system are borne by private parties.[160] The main governmental costs of the system are those associated with maintaining the court systems for patent challenges and enforcement, which by comparison, are minor.[161]

3. Problems with Patents

Despite the distinct benefits of the patent system, scholars have identified a number of problems with it. The principle concern—deadweight loss—results from one of its strengths, the right to exclusion. Exclusion creates artificial scarcity.[162] Deadweight loss results as competitors, who could drive down prices, are restricted by higher prices.[163] Such monopoly pricing opportunites create market distortions.[164] This renders the patent system inefficient because it results in reduced availability or production, resulting in artificially

155. *Id*.

156. *Id*.

157. Brennan et al., *supra* note 127, at 11.

158. Jonathan H. Ashtor, *Redefining "Valuable Patents": Analysis of the Enforcement Value of U.S. Patents*, 18 STAN. TECH. L. REV. 497, 532 (2015).

159. Hemel & Ouellette, *supra* note 122, at 303.

160. *Id*. at 364.

161. *Id*.

162. Roin, *supra* note 118, at 1008.

163. *Id*. at 1023. Of course, these artificially higher prices incentivize innovators. Ted Sichelman, *Patents, Prizes, and Property*, 30 HARV. J. LAW & TECH. 279, 284 (2017).

164. Alberto Galasso et al., *A Theory of Grand Innovation Prizes* 48 RSCH. POL'Y 343–62, 346 (2018).

higher prices.[165] Economists typically consider this deadweight loss from monopoly pricing to exceed the costs of other incentive systems.[166] In some sectors—for example, pharmaceuticals—analysts have found that monopoly power spawns a number of detrimental effects, including high drug prices, inequitable allocation of medicines, and the creation of follow-on drugs with little additional value.[167]

Several procedures are available to minimize deadweight loss. A form of price discrimination, two-part pricing, is one such approach. In this system, a consumer pays an initial fee for the right to acquire units at no additional charge or at a set price.[168] Examples of this pricing scheme include Disneyland[169] and Netflix or Amazon Prime.[170] Similarly, a patent pool typically requires members of the pool to pay a fee for free or discounted access to the patents included in the pool.[171] However, two-part pricing does not completely solve the deadweight issue.[172] The initial fee causes a deadweight loss of its own. For instance, the Disneyland entrance fee will price some potential visitors out of the market. It does, however, allow those who do pay admission to avoid the deadweight loss from monopoly pricing.[173]

Another approach to address deadweight loss involves governmental efforts to reduce the effects of deadweight losses. The government could directly reduce deadweight by subsidizing purchases of the invention or its products, or indirectly reduce it by providing tax credits for such purchases.[174] Alternatively, or in addition, the

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165. Mandel, *Innovation Rewards, supra* note 147, at 309.

166. Roin, *supra* note 118, at 1026. In general, the other systems shift the costs of R&D to the taxpayers (grants, prizes and tax credits are funded by the government). Hemel & Ouellette, *supra* note 122, at 303. Prizes also have significant administrative costs. Spulber, *supra* note 144, at 9–10.

167. Marlynn Wei, *Should Prizes Replace Patents - A Critique of the Medical Innovation Prize Act of 2005*, 13 B.U. J. SCI. & TECH. L. 25, 26 (2007).

168. Roin, *supra* note 118, at 1047.

169. Disneyland charges an admission fee, and then park visitors can enjoy the park's rides at no additional cost. *Id*. at 1047–48.

170. Netflix and Amazon Prime charge a monthly fee for unlimited access to their inventory of films and television shows. *Id*. at 1048.

171. *Id*. at 1048. For proposals to apply patent pools or commons to climate engineering inventions, *see* Anthony E. Chavez, *Exclusive Rights to Saving the Planet: The Patenting of Geoengineering Inventions*, 13 NW. J. TECH. & INTELL. PROP. 1, 9.12 (2015), and Jesse L. Reynolds et al., *Solar Climate Engineering and Intellectual Property: Toward a Research Commons*, 18 MINN. J.L. SCI. & TECH. 1 (2017).

172. Roin, *supra* note 118, at 1048.

173. *Id*.

174. *Id*. at 1051.

government could also impose price controls on these items.[175] Of course, substantial price controls run the risk of reducing the patent system's primary incentive of monopoly pricing. Furthermore, these mechanisms minimize the effect of market forces as incentives for innovation.[176]

The ability to exclude under the patent system also may discourage follow-on inventions.[177] Despite the benefits of invention disclosure, empirical evidence nevertheless suggests that the patent system discourages subsequent innovations.[178] Economists have found that the restrictions of the patent system may impede both follow-on research and subsequent innovations.[179]

Another strength of the patent system, reliance upon markets, may also prove to be a shortcoming. Market valuation of patents is beneficial only if the market is capable of recognizing the value of innovations. However, consumers' willingness to pay for an innovation often does not reflect its true social value.[180] This disconnection between social value and market value often arises with innovations whose value is primarily environmental.[181]

B. Prizes

One mechanism to incentivize research that is currently undergoing a renaissance is prizes. Prizes were used extensively in several high-profile circumstances in the 18th, 19th, and early part of the 20th Centuries, but then patents became the incentive of choice. In retrospect, many commentators criticized the effectiveness of earlier prizes and proposed modifications that would enhance their effectiveness. A recent array of prize awards has given new life to this incentive mechanism.

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175. *Id*. at 1052.

176. *Id*. at 1053.

177. Follow-on inventions are those that relate to previous innovations and discoveries and are thus a part of a cumulative process. Clancy & Moschini, *supra* note 130, at 211.

178. Williams, *supra* note 134, at 7.

179. *Id*. at 8.

180. Roin, *supra* note 118, at 1029.

181. Gregory N. Mandel, *Promoting Environmental Innovation with Intellectual Property Innovation: A New Basis for Patent Rewards*, 24 TEMP. J. SCI. TECH. & ENTVTL. L. 51, 58 (2005).

1. The Fundamentals of Prizes

A prize is a payment offered to an innovator who develops an invention satisfying specified criteria.[182] Typically, the organizer (a government or private party) of the prize sets the amount and terms of the award before prospective inventors have commenced investment into their research; then, the prize goes to the inventor who successfully met the criteria.[183] Since prizes reward innovators for their efforts, prizes often require innovators to place their inventions in the public domain, thereby avoiding the deadweight loss of patents.[184] Some prizes, though, allow inventors to retain their intellectual property rights.[185]

Prizes require clear, prespecified criteria.[186] Prizes typically reward either the person or team that first satisfies the criteria or performs the best by a specified date.[187] Nevertheless, prize organizers may find that, as competitors begin working on their innovations, issues not initially foreseen may arise. For instance, their work may demonstrate that certain criteria may not be feasible or become obsolete through technological innovation.[188] As a result, prizes will operate most smoothly if their organizers incorporate three considerations into their structures – transparency,[189] iteration,[190] and nested decision making.[191]

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182. Nancy Gallini & Suzanne Scotchmer, *Intellectual Property: When Is It the Best Incentive System?*, INTELL. PROP. 53 (2002).

183. Burstein & Murray, *supra* note 128, at 402.

184. Clancy & Moschini, *supra* note 130, at 225. Government prizes, of course, have their own deadweight loss resulting from the taxation required to finance them. Hemel & Ouellette, *supra* note 122, at 314.

185. For instance, in its COMPETES Act, the federal government allows inventors to secure their patent rights. Burstein & Murray, *supra* note 128, at 411. Similarly, grand innovation prizes, such as those organized by the X Prize Foundation, also enable inventors to pursue their patent rights. Galasso et al., *supra* note 164, at 343.

186. Henry G. Grabowski et al., *The Roles of Patents and Research and Development Incentives in Biopharmaceutical Innovation*, HEALTH AFFIARS 308 (February 2015).

187. Brennan et al., *supra* note 127, at 10.

188. Burstein & Murray, *supra* note 128, at 427.

189. *Id*. at 438. Transparency is necessary because of the dynamic nature of the innovation process and the possibility that the organizers may need to revise the rules of the competition as the knowledge of the objective develops. *Id*.

190. Iteration will ensure that the organizers routinely and systematically review and revisit requirements in light of new information as the competition proceeds. *Id*. at 439.

191. With nested decision making, fundamental rules of the competition remain unchanged, while secondary rules are susceptible to modification in light of subsequent developments. *Id*. at 440.

When prize organizers have sufficient *ex ante* information about the type of invention sought and its market value, then prizes have certain advantages over other mechanisms used to incentivize innovation.[192] If prize organizers can estimate the innovations' value with some certainty, then prizes can provide the *ex ante* incentive of patents without the *ex post* detriment of deadweight loss.[193] Furthermore, the need to identify the particular invention makes them especially well suited to incentivizing applied rather than basic research.[194]

Some organizers award their prizes *ex post*. Organizers establish these "blue sky" prizes *ex post* for inventions for which *ex ante* prizes did not exist.[195] These blue sky, or "innovation," prizes reward innovations that satisfy particular criteria.[196] Having compensated inventors for their development, innovation prizes typically then place the innovation into the public domain, thereby avoiding the deadweight loss associated with the patenting of the invention.[197]

2. Prizes through History

The use of prizes to incentivize innovation has a history dating back for centuries. Indeed, they used to be the primary means to incentivize innovative activity. They receded with the rise of the patent system. Nevertheless, they have experienced a resurgence in recent decades.

The English Parliament passed one of the earliest and most prominent *ex ante* prizes in the Longitude Act of 1714.[198] The bill provided £20,000 for a means to determine longitude while at sea.[199] At the time of the passage of the act, everyone assumed that the

192. Adler, *supra* note 149, at 17.

193. Clancy & Moschini, *supra* note 130, at 232.

194. Adler, *supra* note 149, at 17–18.

195. *Id*. at 13.

196. Clancy & Moschini, *supra* note 130, at 225.

197. *Id*.

198. Khan, *supra* note 126, at 635.

199. Dava Sobel, LONGITUDE 53 (1995). In a practice that future prizes would often follow, the Longitude Act actually provided for three prizes with decreasing value, from £20,000, £15,000, and £10,000. To receive the top prize, the submission needed to be able to determine longitude accurately within one-half of a degree; the middle prize required accuracy only to two-thirds of a degress; and the third prize only to one degree. *Id*.

winning device would rely upon astronomical data.[200] However, John Harrison, a watchmaker, eventually won the prize by inventing a clock that utilized an especially accurate measure of time to determine a ship's position at sea.[201] Harrison, poor and uneducated, did not actually receive his prize for 47 years.[202] The Act established the Board of Longitude, a prize committee consisting of scientists, naval officers, and government officials, to disburse the prize funds.[203] The Board delayed awarding Harrison his prize while attempting to establish that solutions premised upon astronomy were more accurate.[204] He eventually needed to seek redress from the King and Parliament to receive a partial award.[205]

Despite this uneven experience, *ex ante* prizes flourished throughout the 18th and 19th Centuries.[206] Both the French and English Royal Academies of Sciences offered numerous prizes.[207] Many prominent names are associated with prizes, including James Madison,[208] Napoleon Bonaparte,[209] and Charles Lindbergh.[210]

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200. Adler, *supra* note 149, at 20.

201. *Id*. at 21.

202. Khan, *supra* note 126, at 635.

203. Sobel, *supra* note 199, at 54.

204. Among the tactics employed by the board to delay the awarding of the prize to Harrison: the Board required a second oceanic trip, rather than the one identified in the Longitude Act, to demonstrate the clock's accuracy; the manufacture of two duplicates of the successful device; and subjection to ten months of additional testing. *Id.* at 123–35.

205. Gallini & Scotchmer, *supra* note 182, at 72, n.2. When informed of the travails of Harrison and his family, King George III is reported as having exclaimed, "These people have been cruelly treated." Sobel, *supra* note 199, at 147. Despite the intervention of the crown and the legislature, Harrison technically never received the full prize to be provided pursuant to the Longitude Act; instead, Parliament awarded a sum comparable to the amount due to him from the Board. *Id*. at 149.

206. Hemel & Ouellette, *supra* note 122, at 317. *Ex post* prizes date back even earlier, to at least the 16th Century. Fiona Murray, Scott Stern, Georgina Campbell, & Alan MacCormack, *Grand Innovation Prizes: A Theoretical, Normative, and Empirical Evaluation*, RESEARCH POLICY 41 (2012) 1779–92, 1780.

207. Adler, *supra* note 149, at 21.

208. During the Constitutional Convention, Madison proposed the inclusion of a prize system, which presumably lost out to the Intellectual Property Clause. Roin, *supra* note 118, at 1021.

209. Napoleon offered a prize of ₣12,000 (approximately $4.5 million in 2017) for a means to preserve food (to help feed his army). In 1795, Nicholas Appert won the prize for a process of sealing meat in glass containers, in a procedure that preceded current day canning procedures. Carol Ann Rinzler, IS IT SAFE TO KISS MY CAT?: AND OTHER QUESTIONS YOU WERE AFRAID TO ASK 29 (2017).

210. Lindbergh's famous transatlantic flight responded to the 1919 Orteig Prize. Despite the conventional wisdom at the time that the flight could only be made by a sizable crew in a multi-engine plane, Lindbergh successfully flew solo in a single-engine plane. Adler, *supra* note 149, at 23–24.

Nevertheless, interest in using the prize mechanism waned. The French Academy, which was largely a model for societies in other countries, suffered a number of contentious disputes concerning its prizes.[211] More generally, a number of issues came to characterize prizes. The awarding of prizes seemed haphazard at best, appearing to result from bias, institutional capture, lobbying, and marketing.[212] Maybe even more damning, many of the most significant inventions of this period did not result from the prize system.[213]

3. Recent Developments in Prizes

Despite the problems that vexed earlier prize organizers, prizes have recently made a comeback. Starting in the 1990's, philanthropists and private parties established several prominent prizes.[214] In this century, the federal government also has begun to use prizes to incentivize research.[215] As a result, a number of both private and public efforts have arisen in the past 25 years.

The 21st Century has witnessed the establishment of a number of high profile and successful prizes. The X Prize Foundation has established many of the most prominent prizes in the past quarter century.[216] The Foundation is a nonprofit organization dedicated to developing grand innovation prizes that lead to radical breakthroughs to benefit humanity.[217] Grand innovation prizes typically offer large

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211. Wei, *supra* note 167, at 29.

212. Khan, *Inventing Prizes*, *supra* note 126, at 659–60.

213. *Id*. at 660. Conversely, an analysis of prizes awarded by the Royal Agricultural Society from 1839 to 1939 suggests that the awarding of prizes resulted in an increase in related patents. Petra Moser & Tom Nicholas, *Prizes, Publicity and Patents: Non-Monetary Awards as a Mechanism to Encourage Innovation*, J. INDUSTRIAL ECON. 785, Vol. LXI (2013).

214. Adler, *supra* note 149, at 24.

215. Hemel & Ouellette, *supra* note 122, at 317.

216. Besides the X Prize Foundation prizes, groups organized several other notewothy prize competitions in the past two decades. For instance, in 2009, Netflix sponsored a $1 million prize. Brennan et al., *supra* note 127, at 1. The award, which sought a better algorithm to recommend content to its customers, attracted several thousand participants. Burstein & Murray, *supra* note 128, at 403. Another prize, organized by RSA Security, offered $250,000 for a development that it could use to improve its encryption software. Adler, *supra* note 149, at 24. Recently, Elon Musk announced a $100 million prize to be awarded for the best technology to capture atmospheric carbon. Reuters Staff, *Elon Musk to Offer $100 Million Prize for 'Best' Carbon Capture Tech*, REUTERS (January 21, 2021), https://www.reuters.com/article/us-usa-musk-carbon-capture/elon-musk-to-offer-100-million-prize-for-best-carbon-capture-tech-idUSKBN29R024.

217. Burstein & Murray, *supra* note 128, at 419.

monetary awards for achieving predetermined performance requirements.[218] Of particular note, they usually do not bar prize winners from securing patent rights.[219]

Three X prize competitions are particularly informative here: the Ansari X Prize, the Progressive Insurance Automotive X Prize, and the NRG COSIA Carbon X Prize. In 1996, the Foundation offered the $10 million Ansari X Prize to the first nongovernmental entity to successfully develop a spacecraft. The ship needed to be able to carry three people 100 kilometers above the earth's surface twice within two weeks.[220] Eight years later, the team that built SpaceShipOne accomplished these objectives and received the award.[221] All told, 26 teams participated in the international competition, collectively investing $100 million into commercial space flight research.[222] Thus, the prize inspired ten times as much in R&D expenditures.

The X Prize Foundation subsequently established the Progressive Insurance Automotive X Prize in 2006 to encourage the development of a fuel-efficient car.[223] This prize demonstrated a number of issues that can arise with prizes. First, the *ex ante* development of technical specifications to define the prize requirements was particularly challenging.[224] The requirements for a successful prize needed to be clear enough for competitors to follow yet flexible enough to adapt to technological developments.[225] The terms of the prize provided:

> A ten million dollar cash purse will be awarded to the teams that win a long-distance stage race for clean, production-capable vehicles that exceed 100 miles-per-gallon energy equivalent.[226]

Despite the brevity of this description, it incorporates a number of

218. Galasso et al., *supra* note 164, at 343.

219. *Id*. In particular, the X Prize Foundation disavows any interest in taking the intellectual property of competitors. Murray, *supra* note 206, at 1787. Interestingly, this approach diverges from traditional prize theory, which views prizes as an alternative to patents and a means to avoid their deadweight loss. *Id*. Not surprisingly, analysis suggests that more robust results occur when prizes allow winners to retain their patent rights. Galasso et al., *supra* note 164, at 351.

220. Hemel & Ouellette, *supra* note 122, at 317.

221. Burstein & Murray, *supra* note 128, at 403.

222. *Id*.

223. *Id*. at 419.

224. Galasso et al., *supra* note 164, at 345, n.4.

225. Burstein & Murray, *supra* note 128, at 424.

226. *Id*. at 419.

complicated concepts. For example, "clean, production-ready" indicates that submissions must satisfy vehicle safety standards, be capable of manufacture at scale, and include the features typical in modern cars.[227] In addition, because of the dynamic nature of this field, the Foundation realized that it might need to alter the rules to take into account technological obsolescence or advancements rendering initial pararmeters irrelevant.[228] Third, the breadth and flexibility of the rules became a source of contention because, as with rules for prizes from preceding centuries, flexible rules led to inconsistent applications and lobbying.[229]

Beyond these issues, the Auto X Prize experience demonstrated other complications that could arise during the pendency of the prize. For instance, the competition included a staging goal— a requirement that competitors satisfy a particular requirement to continue in the competition. The initial standard, however, proved to be too technologically demanding and needed to be revised.[230] Another unforeseen issue involved a divergence in designs, which required the organizers to divide the competition into classes.[231]

The NRG COSIA Carbon X Prize is offering $20 million for breakthrough technologies to convert carbon dioxide emissions into usable products.[232] The utility NRG and Canada's Oil Sands Innovation Alliance (COSIA) are funding the prize.[233] The prize seeks to accelerate the development of carbon utilization technologies.[234] Criteria include the amount of carbon converted into products and the net value of those products.[235] The organizers will divide $20 million in prize funds into $5 million in milestone prizes and $15 million in grand prizes.[236]

In the past two decades, the United States government also

227. *Id*. at 419–20. The organizers included this last requirement because they realized that, in prior competitions for hyper-efficient cars, the submissions often looked like "rolling coffins." Murray, *supra* note 206, at 1785.

228. Burstein & Murray, *supra* note 128, at 427–28.

229. *Id*. at 430–31.

230. *Id*. at 434.

231. *Id*.

232. *X Prize Foundation, Turning CO_2 Into Products*, available at https://www.xprize.org/prizes/carbon, last visited July 17, 2020.

233. Bobeck, Peace, Ahmad, & Munson, *supra* note 17, at 3.

234. NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, and MED., GASEOUS CARBON WASTE STREAMS UTILIZATION: STATUS AND RESEARCH NEEDS 202 (2019).

235. *Id*. Other criteria include the amount of freshwater and land necessitated by their manufacture. *Id*.

236. *Id*. at 226.

began using prizes to encourage innovation.[237] The National Academies of Sciences (NAS) urged the United States in 1999 to utilize prizes to encourage technological innovations.[238] In 2004, the Defense Advanced Research Project Agency (DARPA) offered a $1 million prize for an autonomous land vehicle that could satisfy particular requirements, and in 2006 NASA announced three prize competitions.[239] By 2009, NASA and the Departments of Defense and of Energy had established combined prizes exceeding $35 million.[240] In that year, the Office of Management and Budget encouraged all federal agencies to use prizes to support technological innovation.[241]

Congress also began supporting prizes. The Energy Policy Act of 2005 authorized the National Science Foundation to establish cash prizes of up to $10 million for breakthrough energy technologies.[242] The next year Congress approved legislation to require the National Science Foundation to establish a series of prizes to encourage technological innovation.[243] These developments set the groundwork for the 2010 America COMPETES (Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science) Reauthorization Act.[244] The COMPETES Act authorizes all federal agencies to award prizes to stimulate innovation that may further the mission of the agency.[245] It also identifies a number of criteria that each prize must include.[246] Between 2010 and 2020, federal agencies have conducted nearly 1,000 prize contests, and the total amount offered by the prizes rose from fiscal years 2011 to 2018 from $247,000 to $37 million.[247]

Congress has also considered a bill to use prizes to support carbon capture development. The USE IT (Utilizing Significant Emissions

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237. A long-standing provision mandating prizes for innovations has applied to atomic energy inventions. For national security reasons, individuals who develop inventions in this field may not receive patents, so Congress enabled the Patent Compensation Board to choose to award them a prize reward. Mandel, *Innovation Rewards, supra* note 147, at 317.

238. Hemel & Ouellette, *supra* note 122, at 317.

239. Murray, Stern, Campbell, & MacCormack, *supra* note 206, at 1781.

240. Hemel & Ouellette, *supra* note 122, at 317–18.

241. Murray, Stern, Campbell, & MacCormack, *supra* note 206, at 1781.

242. Adler, *supra* note 149, at 26.

243. Brennan et al., *supra* note 127, at 2.

244. Spulber, *supra* note 144, at 2, n.4.

245. Burstein & Murray, *supra* note 128, at 404.

246. Spulber, *supra* note 144, at 2, n.4. Included with certain basic requirements (subject, eligibility rules, and prize amount) is the delineation of the basis for selecting winning submissions. *Id*.

247. Marcy E. Gallo, FED. PRIZE COMPETITIONS i (2020).

with Innovative Technologies) Act was reintroduced in Congress in 2019.[248] The bill supports research on carbon utilization and direct air capture and facilitates their permitting and development.[249] It also directs the Environmental Protection Agency (EPA) and the Department of Energy to establish a program of financial prizes for direct air capture technologies.[250] It conditions the receiving of any such award upon the vesting in the United States of any intellectual property.[251] The USE IT Act does not mandate (or even mention) an awards program for carbon utilization. Instead, it requires EPA and DOE to initiate a carbon utilization R&D program and to support it by providing technical and financial assistance, though it does not specify the particular type or amount of financial assistance.[252] The Senate did not act on the USE IT Act bill, but other, enacted bills included several of its provisions.[253]

4. The Benefits of Prizes

Analysts have identified a number of benefits that prizes have over other incentive systems, especially patents. A primary advantage is that prizes can encourage researching technologies that markets do not value sufficiently.[254] Markets fail to encourage the development of technologies whose market prices do not reflect their value.[255] Prizes (and grants) "reward innovations that 'are publicly valued but not privately marketable.'"[256] A government prize, for instance, is essentially a government intervention into the markets where they have failed to sufficiently incentivize a public good.[257] Prizes are also

248. *Senators Reintroduce USE IT Act to Promote Carbon Capture Research and Development*, U.S. SENATE COMM. ON ENV'T & PUB. WORKS (February 7, 2019), available at https://www.epw.senate.gov/public/index.cfm/press-releases-republican?ID=A6871F9E-F13B-48E4-82A0-74D983B6902D.

249. H. R. 1166 at 1 (2019). The bill defines "direct air capture" as a technology or system that a facility uses to capture carbon dioxide directly from the air. *Id*. at Sec. 101(6)(B)(i)(III)(aa).

250. *Id*. at Sec. 101(6)(B)(ii)(I).

251. *Id*. at Sec. 101(6)(B)(iv)(I).

252. *Id*. at Sec. 101(6)(C)(iii)-(iv).

253. Govtrack, S. 383 (116th): USE IT Act, last visited July 30, 2021, available at https://www.govtrack.us/congress/bills/116/s383.

254. A similar advantage is that prizes can reward innovations that are not patentable. Brennan et al., *supra* note 127, at 27.

255. *Id*. at 447.

256. Adler, *supra* note 149, at 14. An advantage that prizes have over grants, however, is that prizes reward success, while grants are not contingent upon results. Grabowski et al., *supra* note 186, at 308.

257. Wei, *supra* note 167, at 27.

well suited to encourage high-risk research on technologies that are still at their earliest stages.[258] Similarly, they might also be well suited to encouraging research in circumstances where scientific opinion is divided concerning the appropriate path to direct technological development.[259] In other words, prizes fit circumstances where goals are clear, but the best paths to achieve them are less certain.[260] A number of competitions have demonstrated this pattern. Specifically, the Longitude Bill, the Netflix Prize, and the Progressive Insurance Automotive X Prize all involved identifiable goals where the means to achieve them were uncertain.[261] By establishing criteria that encourage research in particular areas, prizes can offer *ex ante* incentives to pursue a targeted objective.[262] Finally, by setting criteria that suggest a particular result, organizers can signal the importance of a particular issue.[263]

Prizes also avoid the deadweight loss of patents.[264] Unlike the X Prize Foundation's provisions, organizers of other prizes usually require winners of traditional prizes to place their intellectual property into the public domain.[265] Consequently, if the proceeds from prizes are comparable to the returns inventors would receive from patent rights, then inventors receive fair compensation while the public gains ready access to their inventions without incurring the deadweight loss of monopoly patent rights.[266] In programs like those of the X Prize Foundation, which allow innovators to retain their patent rights, the prizes augment the rewards of the patent system.[267] This may be especially helpful where markets do not price in the social value of innovations because the prizes can help to close the gap between investment cost and market compensation.[268]

Another advantage of prizes is that they often broaden the pool of

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258. Williams, *supra* note 134, at 10.

259. *Id*. at 11.

260. Burstein & Murray, *supra* note 128, at 415.

261. *Id*. at 449–50. Also characteristic of these competitions, and an important consideration that favors the use of the prize mechanism, was the fact that certain potential innovators were identifiable, but other possible winners were not. *Id*.

262. Wei, *supra* note 167, at 27.

263. *Id*.

264. Another efficiency benefit of prizes – when compared to grants, which are discussed next – is that prizes do not require researchers to prepare applications, comply with eligibility requirements, or satisfy imposed restrictions or deadlines. Adler, *supra* note 149, at 14-15.

265. Burstein & Murray, *supra* note 128, at 410.

266. *Id*.

267. Adler, *supra* note 149, at 15.

268. *Id*.

prospective innovators. Prizes attract persons who might not otherwise engage in commercial efforts[269] or who might not otherwise have pursued a particular field.[270] The competitive nature of prizes may also attract new parties interested in pursuing the awards.[271] As with the Longitude Act, prizes can attract parties who might normally not be among the anticipated pool of prospective inventors.[272] Also, by broadening the range of participants in the competition, prizes bring the advantages of diversification to the efforts, thereby increasing the likelihood that the competition will generate solutions to the problem.[273] Prizes broaden the pool of participants in part because they also bring attention to their subject matter.[274]

The publicity surrounding prizes appears to be a significant advantage that they provide. Prizes can both generate interest in a topic and add to the prestige of participants.[275] Indeed, historical analysis suggests that the publicity from prizes without cash awards can encourage innovation.[276] One result of publicity is that it attracts additional inventors to the subject.[277] Furthermore, prizes often signal to other possible inventors the significance of innovation in a particular area.[278]

Unlike patents, prizes do not impede – and can support – follow-on innovations. As discussed previously, the exclusive rights and monopoly pricing of the patent system can deter follow-on innovations.[279] Empirical evidence indicating that patents deter such innovations suggests that prizes would be more favorable to them.[280] Similarly, assuming that large awards encourage substantial research efforts for breakthrough inventions, organizers can use a series of smaller prizes to encourage follow-on inventions.[281]

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269. Brennan et al., *supra* note 127, at 14.

270. Moser & Nicholas, *supra* note 213, at 785.

271. Adler, *supra* note 149, at 16.

272. Grabowski et al., *supra* note 186, at 308. Of course, Harrison's invention of a solution that satisfied the Longitude Act is the classic example of a person developing a solution – a timepiece – that the organizers of the competition had not anticipated. *See supra* section II.B.2.

273. Adler, *supra* note 149, at 33.

274. *Id*. at 17.

275. *Id*.

276. Moser & Nicholas, *supra* note 213, at 785.

277. *Id*.

278. *Id*. at 786.

279. *See supra* nn.177–79 and accompanying text.

280. Williams, *supra* note 134, at 7–8.

281. Moser & Nicholas, *supra* note 213, at 786.

5. The Drawbacks of Prizes

Despite the many advantages that prizes have over other incentive mechanisms, they also raise some notable concerns. Of course, a key draw of prizes is their cash awards. Determining this amount, however, can be difficult.[282] To accurately value awards, their organizers require sufficient information to approximate inventions' market and social value.[283] In some instances, doing so requires the prize organizers to have access to information relevant to the value of inventions. Often such data is not readily available,[284] and governmental and nonprofit organizers are especially unlikely to have it.[285] Organizers do not need perfect information, but they do need to be able to estimate eventual consumption comparably to projections by prospective competitors.[286]

The social value of an invention, especially relevant in the context of CCU, is typically difficult to calculate. By its nature, social value is difficult to estimate; it can be particularly difficult when a novel invention or process is involved.[287] Failing to price the award correctly can create problems. If the organizers price awards too low, then they will not incentivize sufficient innovation efforts; if they set the amounts too high, then competitions risk duplication of efforts, possibly leading to favoritism and other issues in the selection process.[288]

Unique pricing and efficiency issues arise with government prizes. Although a primary argument in favor of prizes over patents is the avoidance of intellectual property's deadweight loss, the overall reduction of deadweight loss may not be as large as the elimination of monopoly pricing might suggest.[289] Moreover, governments typically fund their prizes through taxes, which can have their own deadweight effects.[290] In general, however, economists estimate the deadweight

282. Adler, *supra* note 149, at 18.

283. V.V. Chari et al., *Prizes and Patents: Using Market Signals to Provide Incentives for Innovations*, J. ECON. THEORY 147 (2012) 781–801, 782.

284. *Id*.

285. Roin, *supra* note 118, at 1035.

286. *Id*. at 1038.

287. *Id*. at 1035.

288. Park, *supra* note 132, at 203.

289. Roin, *supra* note 118, at 1061–62.

290. Spulber, *supra* note 144, at 9–10. These deadweight effects include the impacts from sales or income taxes. The resulting higher prices may cause some potential consumers to leave

loss from monopoly pricing to be worse.[291]

As suggested previously, prizes' criteria and their application can cause problems. Prizes function the smoothest when organizers can identify a specific problem and can define their criteria for satisfying the competition clearly.[292] To many, the "primary lesson" from the Longitude competition was that the ambiguities in the competition criteria led to the difficulties Harrison encountered in receiving his award.[293] Criteria must be clear and minimize subjectivity, yet be flexible.[294] Of course, all of this must be done in the context of technological development, which could render certain criteria obsolete or irrelevant.[295] As with the Longitude Act experience, prizes with unclear criteria can generate unwanted controversy.[296] The Longitude experience also suggests that a clear enforcement procedure may be necessary to resolve disputes timely.[297]

From an economics perspective, prizes can be inefficient. The broad participation that they stimulate can be a detriment. Essentially, prizes encourage multiple parties to work towards the same innovation.[298] Furthermore, collective resources expended in the pursuit of prize awards can exceed their values.[299] Conversely, the patent system enables sequential development, as disclosure provides follow-on inventors with access to the results of others' work. Then, they can work around these innovations or direct their efforts to new inventions.[300]

A significant commonality between prizes and patents is that both systems provide no financial support for innovators during their research and development work. This can be especially problematic

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the market. Roin, *supra* note 118, at 1026.

291. Roin, *supra* note 118, at 1026.

292. Mandel, *Innovation Rewards, supra* note 147, at 321. This suggests that prizes may not be well suited for problems that are not easily defined and necessitate basic research. Adler, *supra* note 149, at 35. One analysis concluded that prizes could still be used in such circumstances, but they should follow the grand innovation prize model (such as the X Prize competitions) – the winners of the prize awards retain their intellectual property rights. Galasso et al., *supra* note 164, at 351.

293. Burstein & Murray, *supra* note 128, at 413–14.

294. *Id*. at 424.

295. *Id*. at 427.

296. Adler, *supra* note 149, at 18.

297. Gallini & Scotchmer, *supra* note 182, at 72, n.2.

298. Park, *supra* note 132, at 204.

299. Adler, *supra* note 149, at 16. This is another perspective on the $100 million total spent by 26 parties in the hope of winning the $10 million Ansari X Prize. *See supra* at Section II.B.3.

300. Park, *supra* note 132, at 204.

for researchers who do not have the resources to self-fund or whose work requires costly equipment or materials.[301]

C. Grants

1. The Basics of Grants

Another tool to incentivize research and development is grants. Indeed, the federal government provides most of its financial support for research actvitiy in the form of grants.[302] Government grants provide a substitute for private funding of research.[303] Essentially, they shift the funding of research from private sources to public ones (taxpayers).[304]

Government grants finance much of today's basic research.[305] This is not surprising. Conceptual knowledge is not patentable, and the time lag before its application renders it difficult for markets to value.[306] Furthermore, since the results of basic research are uncertain, disconnecting the link between results and compensation facilitates the implementation of this work.[307] Indeed, the receipt of grants is often essential for certain research to proceed at all.[308] Even in later stages, grants can be the superior incentive mechanism. When the need for basic research arises in later stages of applied research, grants still excel. This research tends to be time consuming and distracting from the primary task.[309]

Administering grants requires the government to acquire sufficient information to make allocation decisions.[310] Factors that complicate decisionmaking include the inherent uncertainty of the innovation process[311] and information asymmetry.[312] Governmental

301. Adler, *supra* note 149, at 35.
302. *Id*. at 3.
303. Grabowski et al., *supra* note 186, at 308.
304. *Id*.
305. Clancy & Moschini, *supra* note 130, at 233.
306. *Id*. at 215.
307. *Id*. at 216.
308. *Id*. at 219.
309. Williams, *supra* note 134, at 11.
310. Grabowski et al., *supra* note 186, at 308.
311. Burstein & Murray, *supra* note 128, at 432–33.
312. *Id*. at 435.

agencies can overcome these concerns by utilizing both high-level policymaking and peer review. Setting policy at upper levels of agencies allows for the setting of priorities and political accountability; peer review assures that members of the pertinent scientific communities decide the awarding of grants.[313]

2. <u>The Benefits of Grants</u>

By providing financial support to conduct research, grants effectively reduce the costs of this work.[314] This is especially important for certain researchers, including those who do not have sufficient resources,[315] do not have income that can be offset by tax credits,[316] or are conducting research that requires costly equipment or the construction of demonstration projects.[317] Furthermore, unlike patents, which reward whatever inventions on which researchers decided to expend effort, grants provide a means for the government to direct research.[318]

In general, researchers and scientific societies prefer grants for three reasons. First, government bureaucrats and researchers alike find them easier to administer. Second, grants afford administrators more discretion in awarding them.[319] From the government's perspective, grants can be an effective means of directing and generating research leads.[320] Finally, for researchers, grants reduce their costs and do not condition compensation upon the success of their work.[321]

3. <u>The Problems with Grants</u>

313. *Id*. at 451–52.

314. Hemel & Ouellette, *supra* note 122, at 311.

315. Clancy & Moschini, *supra* note 130, at 219 (noting that while the government intends grants to cover the costs of research, they often provide part of researchers' compensation, too).

316. Hemel & Ouellette, *supra* note 122, at 337.

317. Adler, *supra* note 149, at 18.

318. Wei, *supra* note 167, at 45.

319. Adler, *supra* note 149, at 23.

320. Williams, *supra* note 134, at 10.

321. Clancy & Moschini, *supra* note 130, at 216.

Despite the important role that grants play in innovation, they are not without criticisms. One primary objection regards the process for determining the parties who will receive the grants. The centralized nature of awarding grants limits the range of prospective researchers who might receive funding.[322] This narrowing not only limits the number of parties addressing particular topics, it also reduces the likelihood that the grants will generate viable solutions.[323] Furthermore, since grants are upfront payments, unlike with patents and prizes, recipients do not – and cannot – assure that the sought innovation will in fact be developed.[324]

Another related concern involves the selection process for determining grant recipients. Government grants can be susceptible to political pressure.[325] Although grant programs can use peer-review procedures, even expert panels can direct funds suboptimally.[326] Regardless of the merits of selection processes, by their nature *ex ante* grants will pick "winners" and "losers."[327] Even assuming that the process is unbiased, successfully selecting the applicants most likely to succeed can be difficult.[328] Not surprisingly, government programs have had limited success in selecting paths for future innovations.[329]

Government grants also have higher administrative costs than most other incentive mechanisms. Typically, they must comply with federal regulations and agency reporting requirements. These restrictions discourage potential applicants by raising the temporal and financial costs of applying.[330] In some grant programs, the combined administrative burden on the agency and applicants could reach as high as one third of the total grant award.[331]

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322. Adler, *supra* note 149, at 29.

323. *Id*.

324. Mandel, *Innovation Rewards, supra* note 147, at 320.

325. Adler, *supra* note 149, at 29.

326. *Id*. at 34.

327. *Id*. at 29.

328. Wei, *supra* note 167, at 45 (noting difficulties the government has encountered in identifying research that can best improve health care or the best applicant to perform such work).

329. Adler, *supra* note 149, at 37.

330. *Id*. at 31.

331. Hemel & Ouellette, *supra* note 122, at 362. Governmental grant programs also run risks of influence or capture during the seletion process. Adler, *supra* note 149, at 34. These programs often utilize peer-review panels or other mechanisms to avoid these issues. *Id.*

D. Tax Policy

1. Incentivizing R&D through the Tax Code

The government also uses the tax code to encourage research. The tax code contains two primary provisions pertaining to research costs. First, Section 174 of the code allows taxpayers to treat research expenditures as expenses (as opposed to capitalized investments).[332] Alternatively, taxpayers can forgo the Section 174 deduction and instead claim a 20% tax credit under Section 41.[333] This section provides a credit equivalent to the amount of research expenses increased over a base amount.[334] Congress did not make the credit permanent until 2015. Until then, it set expiration periods for the credit.[335] This practice incurred the wrath of businesses because of the resulting inability to plan their expenditures.[336]

State governments also use tax credits to incentivize research.[337] In some instances, European countries have used more targeted tax benefits. For instance, The Netherlands, Belgium, and Hungary have provided tax credits or deductions for salaries of researchers.[338]

2. Strengths and Weaknesses of Using the Tax Code

Analyses of tax credits indicate that they have encouraged taxpayers to spend more on research expenditures than they would

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332. 26 U.S.C. § 174(a)(1). Expensing allows taxpayers/researchers to apply the research expenses against current income. Otherwise, the Tax Code would require that taxpayers capitalize expenditures incurred to create or improve assets with useful lives of more than one year and then depreciate or amortize these expenditures over an extended period of time. Stephen E. Shay et. al., *R&D Tax Incentives: Growth Panacea or Budget Trojan Horse?*, 69 TAX L. REV. 419, 430 (2016).

333. *Id*. at 432.

334. 26 U.S.C. § 41(a). The credit limits its application to expenses that exceed the taxpayers' base amount of research expenditures to ensure that taxpayers receive the credit only for increasing their research costs. Hemel & Ouellette, *supra* note 122, at 324. Taxpayers can apply a tax credit equal to 20% of their research expenditures. *Id*. The credit applies only to some of the expenditures that can be expensed under Section 174. *Id*. at 323.

335. Shay, *supra* note 332, at 434. In fact, Congress allowed the credit to expire for a twelve-month period extending from 1995 to 1996. Graetz, *supra* note 119, at 353, n.17.

336. Shay, *supra* note 332, at 434.

337. Hemel & Ouellette, *supra* note 122, at 325.

338. Noked, *supra* note 119, at 145.

have otherwise.[339] Indeed, Congress designed the credits to produce this particular result. The credits reward only research expenditures that exceed a "base amount" of past research expenditures.[340] Additionally, tax credits and deductions help to elicit information from private actors regarding the expected value of R&D projects.[341] Tax provisions also avoid monopoly costs in markets.[342]

Commentators have criticized research tax provisions on several grounds. A primary criticism is that conclusions about their effectiveness have been unclear. Analyses of R&D tax incentives produce a wide range of estimates of the effect of such incentives in generating new R&D; they also question the cost effectiveness of such an approach.[343] Another concern regarding tax incentives is that they actually only incentivize established entities that have taxable liability, enabling them to make use of the tax deductions or credits.[344] Other entities, such as startups, often have no income against which to apply their deductions or credits.[345] Finally, other problems that hamper government incentives apply here as well. *Ex ante* the government will often be unsure of which innovations to incentivize or be unable to value inventions accurately.[346]

III. PUTTING IT ALL TOGETHER

Each of the four incentive systems can be the optimal approach depending upon the particular set of circumstances involved.[347] The following section will explore more fully the circumstances which favor particular incentives. Then, this article will consider which of these incentives – or combination of incentives – will best encourage research into particular uses of carbon.

339. Guenther, *supra* note 121, at 1.

340. Hemel & Ouellette, *supra* note 122, at 324.

341. *Id*. at 303.

342. *Id*.

343. Graetz, *supra* note 119, at 355. For instance, findings for the benefit-cost ratio for the R&D credit have found ratios ranging from 0.293 to 2.0. *Id*. at 356-57.

344. *See* Shay, *supra* note 332, at 448, n.138 and accompanying text (noting that most of the benefit from corporate R&D tax credits goes to large corporations).

345. *Id*. at 337. When researchers do have excess income against which to apply the credit, then refundable tax credits function comparably to grants. *Id*. at 381.

346. Wei, *supra* note 167, at 45.

347. Galasso et al., *supra* note 164, at 345.

A. Considerations of Markets and Timing

Besides the inherent strengths and weaknesses of these incentive mechanisms, additional considerations impact their effectiveness. Considerations regarding the decisionmakers best positioned to set incentives' values, the best parties to pay for them, and the optimal timing of incentives all impact the determination of optimal incentives. While not determinative, they do suggest which incentives may be most effective in promoting particular innovations.

1. Markets Versus Centralized Decisionmakers

An important consideration in selecting among incentives regards the party that will identify the targeted innovations and set the value of the reward – markets or the government.[348] As noted earlier, patents rely upon markets to drive innovation and its rewards.[349] Markets establish rewards for inventions through price signals. Knowing this, private innovators can choose subjects for research and receive subsidies and rewards for their efforts through the market.[350] On the other hand, prizes, grants, and tax incentives rely upon centralized actors—governments, peer-review panels, foundations, etc.—to determine the direction of innovation and its compensation.[351] Of course, market signals may not encourage certain innovations. When market signals do not reflect social value, then incentives that rely upon them fail to stimulate sufficient innovation.[352]

2. Paying for Innovation

As previously discussed, the parties who value innovations—and, often, pay for them—differ with the particular incentive. Cross subsidization occurs when nonusers of an invention pay the costs of the users.[353] When funded by general revenues, prizes, grants, and tax

348. Zachary Liscow & Quentin Karpilow, *Innovation Snowballing and Climate Law*, 95 WASH. U. L. REV. 387, 429 (2017).

349. *Id*.

350. *Id*.

351. *Id*.

352. Hemel & Ouellette, *supra* note 122, at 328.

353. *Id*. at 348.

credits all involve cross subsidization by nonusers (typically taxpayers).[354] The government can, however, utilize cross subsidization to alter innovation incentives.[355] For instance, it can shift some of the burden normally imposed on taxpayers to users through targeted sales taxes.[356] This is an example of an important concept—decisionmakers can tweak aspects of incentives to alter their typical effects.[357]

A related consideration involves risk. Unfunded researchers pursuing an innovation not covered by a prize bear the entire risk that their efforts will produce an invention generating sufficient demand to assure a sufficient profit, or even to recoup their research costs.[358] Conversely, grants and prizes shift the burden of unsuccessful research onto the funding party (the government or private parties).[359]

3. <u>The Timing of Incentives</u>

Another consideration when choosing among incentive mechanisms is the timing of the benefits provided. The timing of the receipt of funds can be crucial. The financial benefits of grants and tax credits occur *ex ante* the innovation; for prizes and patents, they arrive *ex post*.[360] Even when prizes or patents promise noticeably larger returns, some parties may not be able to wait for *ex post* rewards.[361] Some innovators, especially startups, may have trouble raising capital or lack sufficient income to wait for *ex post* returns.[362] Nonrefundable tax credits also may have limited value to startups or other entities lacking current income.[363] Thus, the decision to utilize an *ex ante* or *ex*

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354. *Id*.

355. *Id*.

356. *Id*. Society utilizes cross subsidization in a number of other contexts, though usually it operates in reverse fashion, with taxpayers subsidizing the costs borne by users of particular services. Examples include subsidies for airline tickets and national park usage, among others. *Id*. at 352.

357. *Id*. at 309.

358. Brennan et al., *supra* note 127, at 20.

359. *Id*. at 25 (illustrating the allocation of risk with different incentive schemes).

360. Hemel & Ouellette, *supra* note 122, at 333.

361. *Id*. at 336.

362. *Id*.

363. *Id*. at 338. Recently, experience with renewable energy tax credits has demonstrated the reduced impact such credits may have. With renewable energy being a relatively new industry, many startups lacked sufficient income to take advantage of production tax credits and investment tax credits provided to the industry. In many instances, developers needed to involve

post reward can limit the parties able to pursue particular innovations.[364] Conversely, if innovators believe that an invention has significant financial potential, the prospect of being restricted to a limited *ex ante* award may not be sufficiently inviting.

B. Patents Versus Prizes or Patents and Prizes

Patents and prizes have been the primary driving forces behind innovations for the past several centuries. Patents played a critical role in the technological development since industrialization;[365] prizes have been instrumental in the development of numerous pivotal inventions before industrialization and in recent decades.[366] Because of their prominence in encouraging innovation, a more thorough review of these differences appears below. In short, patents use markets to reward innovators.[367] Conversely, prizes rely upon organizers to value the award.[368] As this discussion will suggest, the optimal combination will turn on a range of factors.[369]

Despite their differences, or maybe because of them, patents and prizes can work well together. The two incentives need not be mutually exclusive; patents and prizes can be used as complements.[370] Prizes can supplement the return innovators are likely to receive from patents.[371] This can be especially important for innovations that are pursued for their social value, since markets are unlikely to fully recognize that value.[372] Of course, when governments or foundations utilize prizes to

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outside investors to monetize their tax benefits. Molly F. Sherlock, THE RENEWABLE ELECTRICITY PRODUCTION TAX CREDIT: IN BRIEF 1 (November 27, 2018). In such circumstances, a significant portion of the subsidy went to the outside investors and to efforts to identify and attract them. Felix Mormann, *Beyond Tax Credits: Smarter Tax Policy for a Cleaner, More Democratic Energy Future* (*Beyond Tax Credits*), 31 YALE J. ON REG. 303, 324 (2014). As a result, analysts concluded that one dollar of direct cash payment through grants had twice the benefit of one dollar of tax credit. *Id*. at 322.

364. Hemel & Ouellette, *supra* note 122, at 338.

365. Khan, *supra* note 126, at 648.

366. *See supra* Section II.B.2.

367. *See supra* Section II.A.2.

368. *See supra* Section II.B.1.

369. Hemel & Ouellette, *supra* note 122, at 303.

370. Adler, *supra* note 149, at 15. In fact, grants and tax incentives also can serve as complements to patents. The federal tax code, however, does preclude claiming credits for research funded by a grant. Hemel & Ouellette, *supra* note 122, at 316-17.

371. Adler, *supra* note 149, at 15.

372. *Id*.

incentivize innovation, additional methods, such as patents, may still be required for adequate diffusion of the invention. Another such policy is the advance market commitment (AMC).[373] Through an AMC, the government commits to purchase a previously identified quantity of an invention satisfying particular criteria.[374]

Certain other considerations become apparent from a review of these incentives. First, prizes and patents require innovators to shoulder their research costs;[375] tax credits only help offset these costs;[376] grants, however, do provide *ex ante* support to reduce these expenses.[377] Economists, however, consider one of the strengths of patents and prizes is that, as *ex post* incentives, they encourage researchers to direct their efforts to projects with the best prospects.[378] Second, when sufficient information is available to enable prizes and grants to be as effective as patents in stimulating innovation, the former are superior. This is because they avoid the deadweight loss resulting from patents.[379] Conversely, patents do impose the costs of inventions upon their consumers; the other incentives, on the other hand, place their financial burdens on taxpayers.[380]

Of course, governments can combine incentive systems to overcome one method's limitations, to reinforce methods' impacts, or to achieve multiple objectives. For instance, one approach used by

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373. *Id*. at 44.

374. *Id*. AMCs developed to incentivize the production of vaccines for developing countries. Global Health TECHS. COALITION, EXPLORING THE ROLE OF THE U.S. GOVERNMENT IN A FUTURE ADVANCE MARKET COMMITMENT 1, https://www.ghtcoalition.org/pdf/AMC-Policy-Brief.pdf (last visited Sept. 4, 2021). AMCs guarantee a market for an invention at a specific price, *id*., but they do not guarantee that all available products will be purchased. Center for Global Development, *What Is an Advance Market Commitment?*, (February 18, 2005), available at https://www.cgdev.org/blog/what-advance-market-commitment. Thus, they still enable purchasers to select the best product for their purposes, thereby incentivizing inventors to continue innovating. *Id*. AMCs provide a number of economic benefits, too. First, they increase revenues for inventors and reduce their volatility. Vivid Economics, ADVANCE MARKET COMMITMENTS FOR LOW-CARBON DEVELOPMENT: AN ECONOMIC ASSESSMENT 18 (2009). Second, by assuring certainty regarding demand, AMCs provide another means by which to stimulate investment. *Id*. at 16. Finally, AMCs are especially appropriate for products that benefit society, but may not necessarily be profitable. GHTC, *supra* at 3.

375. Adler, *supra* note 149, at 32.

376. *See supra* Section II.D.

377. Hemel & Ouellette, *supra* note 122, at 311.

378. *Id*. at 334.

379. Brian D. Wright, *The Economics of Invention Incentives: Patents, Prizes, and Research Contracts*, 73 THE AM. ECON. REV., 691-707, 703 (1983).

380. Hemel & Ouellette, *supra* note 122, at 303.

several countries is patent boxes.[381] Patent boxes essentially combine patents with tax credits. Specifically, they provide that the government will apply a lower tax rate to profits earned from commercial use of patented innovations.[382] They are thus a form of subsidy applied to income from patents.[383] Patent boxes function similarly to a combination of patents and tax credits. As of 2015, the tax codes of 16 countries—primarily in Europe, but also some in Asia—utilize patent boxes.[384]

Analytically, patent boxes are output-driven tax incentives.[385] Patent boxes involve two elements—their tax subsidy and the subsidy's scope. The subsidy comes either as a deduction or as an exemption from taxable income or as the application of a preferential tax rate to the qualifying patent income.[386] The subsidy's scope regards the kinds of income, such as income from a patent, that qualifies for the specialized treatment.[387] Regardless of the specific procedures, patent boxes effectively increase the return on patented inventions. Governments utilize patent boxes to encourage research and development leading to the patenting of inventions.[388]

Because most nations have enacted their patent boxes after 2007, the available data regarding their effectiveness is limited.[389] Patent boxes do seem likely, however, to increase research activity.[390] They also have had a strong effect in attracting high value patents to the jurisdictions utilizing them.[391] Researchers have concluded that a 1%

381. Another approach used by several European countries is a super deduction for R&D expenses. The super deduction allows taxpayers to deduct as R&D expenses amounts that exceed the actual expenditure. Noked, *supra* note 119, at 116, n.20. Super deduction amounts range from 125% (Austria and the United Kingdom, the latter for large companies) to 150% (Denmark and the United Kingdom, for small companies) to even a double deduction (Hungary and the Czech Republic). Graetz, *supra* note 119, at 353-54. Over time, some of these countries have raised their super deductions. The United Kingdom, for instance, increased its super deductions to 130% and 225%, respectively, while Hungary raised its to 400%. *Id*. at 355.

382. Guenther, *supra* note 121, at 1-2. The name of this tax benefit derives from the box that taxpayers check to indicate that the identified income is sourced from qualifying patents. *Id*. at 2.

383. *Id*. at 1.

384. *Id*. at 3. Efforts in the United States by the House Ways and Means Committee Chair to enact patent boxes were unavailing. Graetz, *supra* note 119, at 369-71.

385. Alstadsæter, *supra* note 140, at 133.

386. Guenther, *supra* note 121, at 1.

387. *Id*.

388. *Id*.

389. *Id*. at 19.

390. *Id*. at 22.

391. Alstadsæter, *supra* note 140, at 135. "High value" patents are those with high earnings

reduction in the tax rate applied to patent-derived income results in a 3% increase in patent applications.[392]

In conclusion, each of the incentives excels in particular situations. Furthermore, under certain circumstances, incentives can be used in combination. This can help to achieve particular objectives or to combine strengths of different policies.

C. Incentivizing CCU in Different Sectors

We can now consider which incentive or combinations of incentives might best encourage research into the potential uses of carbon discussed earlier. Because we utilize concrete in such large quantities,[393] CCU concrete can play a critical role in reducing CO_2 emissions. Fortunately, scientists have completed most of the basic research, and some enterprises have already developed cement carbon utilization methods.[394] However, although processes exist, they remain costly, rendering CCU concrete non-competitive.[395] Thus, innovators need to conduct additional research, not to prove a theoretical concept, but to reduce the costs of a process. Furthermore, this involves a product for which the future market is potentially large, even though the market currently may not fully value its environmental benefits.

For CCU concrete,the criteria for selecting incentives weigh in favor of utilizing a combination of them. While market-based incentives could prove to be lucrative for CCU concrete, they have failed to produce a product that is cost competitive.[396] In part, this may be because the market fails to value sufficiently the environmental

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potential. *Id*. High value patents have actually been more impacted by the tax advantages of patent boxes than have lower value patents. *Id*. at 166.

392. Guenther, *supra* note 121, at 19. However, analyses suggest that some of this increase derives from multinational corporations choosing jurisdictions with patent boxes as homes for their patents. Alstadsæter, *supra* note 140, at 166. Indeed, patent boxes tend to discourage inventors from moving to those jurisdictions. *Id*. at 168. To address this, one proposal involves imposing a local-research requirement to receive the tax benefits of a patent box. Professors Alstadsæter et al*.*, conclude that such a requirement increases the level of local research underlying these patents. *Id*

393. *See supra*, Section I.B.3.a. (noting that concrete is the most used human-made material, and we use it on the same gigaton scale as we emit carbon).

394. Schneider, *supra* note 47, at 12516.

395. *See supra*, n.65 and accompanying text.

396. The "greenest" concretes, those which most reduce CO2 emissions, can cost twice as much as conventional concrete. Lee, *supra* note 46.

benefits of products such as CCU concrete.[397] Accordingly, in light of the significance of this product to CO_2 reduction, utilizing more than a single incentive would be appropriate.

Specifically, offering a prize in addition to preserving intellectual property rights could accelerate development of CCU concrete.[398] Prizes can incentivize R&D investments multiple times larger than the amount of the prize.[399] Furthermore, a prize will bring attention to the need to develop CCU concrete, thereby possibly encouraging the involvement of additional persons who might not otherwise have contemplated this issue.[400] Prizes would also be appropriate since they can incentivize innovations with environmental benefits that the market does not value.[401] Finally, because of the importance of CCU concrete, the government might take additional steps to encourage work in this area. For instance, it could make patents for CCU concrete more valuable by instituting patent boxes—in other words, providing tax credits for income derived from these patents to increase the profitability of these innovations.[402] Another device to increase profitability and thereby encourage such research is the super deduction utilized by many European nations.[403]

CCU fuels raise a series of different challenges. Although they carry the promise of providing the second largest future market for CCU products,[404] they still suffer from gaps of knowledge concerning engineering and processes.[405] Conversion costs of CO_2 into synthetic

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397. Mandel, *supra* note 181, at 58.

398. Adler, *supra* note 149, at 15 (noting that a prize would augment the incentive to innovate already provided by the opportunity to secure a patent).

399. *See supra* notes 220-22 and accompanying text (noting that the $10 million Ansari X Prize incentivized $100 million in related research investments).

400. *See supra* notes 269-74 and accompanying text (recognizing that prizes attract participation by persons who typically would not pursue a particular innovation).

401. Adler, *supra* note 149, at 14.

402. Hemel & Ouellette, *supra* note 122, at 332. Because of the potentially large future market for price-competitive CCU concrete, such patent boxes should probably decline over time to avoid a windfall benefit. Besides incentivizing research to reduce the production costs of this concrete, the government also could implement policies to reduce their effective market price. This could encourage sales and engender cost reductions resulting from economies of scale and learning by doing. *See supra* note 83. These policies could include content mandates that require that specified portions of concrete consist of the carbon capturing type. Alternatively, tax credits or other policies that could reduce the effective purchase price of these products should also be helpful. Such policies could temporarily lower the cost of CCU, thereby increasing its purchase and resulting in the cost benefits of increased scale.

403. *See supra* note 381.

404. Bobeck, *supra* note 17, at 11.

405. The Royal Society, *supra* note 21, at 14.

fuels also remain prohibitive.[406] Since the knowledge gap involves processes, centralized decision makers may not be able to project accurately the eventual value of such developments. Similarly, markets are unlikely to value the environmental benefits of such innovations. Finally, industry is anticipated to pursue these fuels as greater knowledge is gained, which will lower the risk of investing in this research.[407]

Accordingly, *ex ante* incentives, such as grants, that reduce the costs (and the risks) of research would be helpful. Grants can help direct research to specific subjects.[408] Even though some of these technologies and products already exist, their costs still remain prohibitive.[409] As with other CCU products, policies that increase production or temporarily lower prices—mandates,[410] AMCs, and price subsidies—will also be beneficial. Finally, tax credits that reduce the high capital costs of fuel development and processing would also lower the costs, and the risks, of these R&D investments.

While CCU could be used by the chemicals industry, scientists project the domestic market to be limited.[411] Since many established entities participate in the chemicals industry,[412] the need for *ex ante* incentives is reduced. Moreover, the chemical industry is already one of the largest generators of patented inventions.[413] Thus, complementary incentives could help to steer the industry to pursue CCU uses. For instance, tax credits can help reduce the costs of research. Because many enterprises involved in the chemical industry are established businesses, they often have the income that tax credits could offset, providing the necessary incentive.[414] Since the industry

406. Bobeck, *supra* note 17, at 11.

407. Lucci, *supra* note 13, at 5.

408. Wei, *supra* note 167, at 45.

409. Bobeck, *supra* note 17, at 13.

410. Examples of mandates applicable here are the LCFS and AFS requirements implemented by a number of states. *See supra* note 78.

411. Jacobson & Lucas, *supra* note 43, at 4.

412. The domestic chemical industry consists of more than 13,000 firms generating sales exceeding $765 billion. International Trade Administration's Industry & Analysis Unit, Chemical Spotlight: The Chemical Industry in the United States, last visited July 31, 2021, available at https://www.selectusa.gov/chemical-industry-united-states.

413. Alstadsæter, *supra* note 140, at 139.

414. Tax credits for R&D are especially appropriate for an industry represented substantially by large, established interests. Large businesses have several recognized advantages in investing in R&D, including a greater ability to diversify risks, better access to financing, and more resources to apply to patent registration and protection. Shay, *supra* note 332, at 448. Not surprisingly, corporations with revenues exceeding $250 million receive nearly all (84%) of the corporate R&D credit. *Id*. at n.138.

already develops many patentable inventions, the government should encourage the development of CCU-related patents. Patent boxes and super deductions, which would reduce the taxes on income from these taxes, could also help encourage the industry to increase its efforts in this area.

Some algae-based products might most effectively be incentivized by prizes. Prizes are especially appropriate for incentivizing high-risk research on technologies that are still at their earliest stages.[415] Scientists still need to conduct basic research regarding several potential algae applications—such as biofuels and bioplastics—to establish their viability at acceptable costs.[416] Technical challenges and limitations still preclude these avenues.[417] While centralized decision making might not be advantageous, the government might be best positioned to fund this basic research until directions and products become more apparent. Thus, prizes—which encourage a wide range of participation, perspectives, and directions—would be particularly appropriate.[418] Furthermore, because of the uncertainty of the paths forward, prizes have several advantages. First, they are likely to encourage participation by additional persons than might otherwise conduct this research.[419] Second, and related to the first, prizes are more likely to engender a wide range of solutions, including some not contemplated by the prize organizers.[420] Finally, algae uses are still at their initial stages, so prizes are particularly well-suited incentives.[421] Prizes would be superior to patents because of the latter's provision of exclusive rights, which tends to discourage follow-on inventions.[422] Indeed, organizers could even break the prizes into a series of smaller prizes to further encourage follow-on or cumulative inventions.[423]

Scientists have postulated a number of other possible CCU

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415. Williams, *supra* note 134, at 10.

416. Bobeck, *supra* note 17, at vi.

417. NAS, *supra* note 12, at 121.

418. Also, because of the likely involvement of startup entities, methods that reduce *ex ante* the costs of research, such as grants, might be especially helpful. Hemel & Ouellette, *supra* note 122, at 311.

419. Moser & Nicholas, *supra* note 213, at 785.

420. Harrison's clock solution to The Longitude Act's prize and Lindbergh's solo transatlantic flight are two prominent examples of unanticipated solutions to earlier prizes. *See supra*, Section II.B.2.

421. Williams, *supra* note 134, at 10 (noting the appropriateness of prizes for high-risk research on early-stage technologies).

422. Clancy & Moschini, *supra* note 130, at 211.

423. Moser & Nicholas, *supra* note 213, at 786.

applications.[424] However, many of these uses remain theoretical,. so decentralized decisionmaking would be best because no clear direction exists. Effectively, this would track the Carbon X Prize.[425] But, where that prize targeted a method to utilize the greatest amount of carbon possible, this would be targeted more toward novel uses of CCU applications with promise. In other words, the objective is clear but the best approach to achieve that objective is not, which is the ideal situation to utilize prizes.[426] The government also should provide *ex ante* funding, such as grants, to encourage work by startups and other small enterprises to provide a wide range of perspectives and potentially generate diverse uses.[427]

IV. CONCLUSION

Avoiding the worst effects of climate change will require that we undertake a range of actions. CCU can play a significant role, directly and indirectly, in accelerating our efforts to reduce atmospheric carbon. However, before it can play this role, significant advancements are necessary. We have the policy tools to incentivize this research, and we need to implement them soon.

424. *See supra*, Section I.B.3.e (including various food and manufacturing processes, among others).

425. *See supra*, Section II.B.3.

426. Burstein & Murray, *supra* note 128, at 415.

427. Indeed, at least one commentator considers grants to be potentially "the most effective driver for relevant [CCU] research and deployment." Kai Jiang et al., *China's Carbon Capture, Utilization and Storage (CCUS) Policy: A Critical Review*, 119 RENEWABLE AND SUSTAINABLE ENERGY REV., 1-15, 11 (2020).