DRA DAVID PAUL ROSEN & ASSOCIATES
DEVELOPMENT, FINANCE AND POLICY ADVISORS

3527 Mt. Diablo Blvd., #361
Lafayette, California 94549
tel: 510.451.2552
fax: 510.451.2554
david@draconsultants.com
www.draconsultants.com

NET ZERO 2050, CLIMATE CHANGE AND LAND POLICY

Prepared for

LINCOLN INSTITUTE OF LAND POLICY

https://www.lincolninst.edu/

Prepared by

David Rosen, PhD
Nora Lake-Brown

DAVID PAUL ROSEN & ASSOCIATES

http://www.draconsultants.com/

March 28, 2022

DAVID PAUL ROSEN & ASSOCIATES
DEVELOPMENT, FINANCE AND POLICY ADVISORS

TABLE OF CONTENTS

DRA DAVID PAUL ROSEN & ASSOCIATES
DEVELOPMENT, FINANCE AND POLICY ADVISORS

3527 Mt. Diablo Blvd., #361
Lafayette, California 94549
tel: 510.451.2552
fax: 510.451.2554
david@draconsultants.com
www.draconsultants.com

PREFACE

Human civilization faces an existential threat from global warming. Multiple international bodies, both public and private sector, and the global scientific consensus conclude that to avoid the most devastating effects of climate change, the world must limit global warming to 1.5°C by 2100 from pre-industrial levels. There is widespread agreement in the scientific community that limiting global warming to 1.5°C requires global greenhouse gas (GHG) emissions must reach "net zero" by the year 2050. The Net Zero 2050 goal is defined as eliminating new net increases in GHG emissions to the atmosphere.

Achieving this goal will require global cooperation, capital investment, social and economic transformation at unprecedented speed and scale. Mitigating GHG emissions will be necessary to achieving Net Zero 2050, both by the rapid and very large scale reduction in new emissions, and by the removal of GHGs, especially CO2, that are already in the atmosphere. Collectively, the measures needed to achieve Net Zero 2050 frame the Mitigation Agenda.

However, sufficient global warming is baked into the Earth's climate to all but assure devastating impacts: polar ice melt, sea level rise, drought, heat waves, wildfires, hurricanes, storms and floods, food and water insecurity for tens if not hundreds of millions of people. Widespread coastal and inland flooding, famine and climate-caused migration on a historically unprecedented scale are all but unavoidable. Some impacts are now categorized as irreversible. These will vary widely by the degree and pace of global warming, and by geography, population growth and migration. Accordingly, there exists a high degree of uncertainty in planning, costing, and paying for adaptations to the destructive effects of climate change. How cities, agricultural regions, natural conservation and biodiversity habitat adapt to these impacts frames a complex and evolving climate change Adaptation Agenda.

The Lincoln Institute of Land Policy

Land policy and land use are central to mitigating GHG emissions to help achieve Net Zero 2050. Researchers conclude that the land sector can contribute approximately 30 percent per year of the global mitigation needed to achieve Net Zero 2050. Further, many of the adaptation measures climate change requires of governments and the private sector, communities, institutions and individuals must centrally focus on land policy and land use.

The Lincoln Institute of Land Policy (LILP) has commissioned this paper in an effort to better understand how land use and land policy can best contribute to the Mitigation and Adaptation Agendas. Further, the Lincoln Institute seeks to understand how its resources, expertise and capacity may best be deployed to help achieve the Net Zero 2050 goal, and to help communities adapt to climate change.

LILP's mission seeks to improve quality of life through the effective use, taxation, and stewardship of land. The Lincoln Institute researches and recommends creative approaches to land as a suite of solutions to economic, social, and environmental challenges. Through research, education, training, publications, and events, LILP integrates theory and practice to inform public policy decisions worldwide.

LILP organizes its work around the achievement of six goals:

- low-carbon, climate-resilient communities and regions;
- efficient and equitable tax systems;
- reduced poverty and spatial inequality;
- fiscally healthy communities and regions;
- sustainably managed land and water resources; and
- functional land markets and reduced informality.

The Lincoln Institute's activities focus on:

- Research to inform and advance the field of land policy worldwide;
- Capacity building for decision makers and practitioners to adopt effective land policies;
- Fostering recognition of land policy as a tool to address social, economic and environmental challenges.

LILP has global reach, with active practice and partners in Africa, Asia, Latin America and the Caribbean, Europe, the United States and Canada.

Focus of this Paper for LILP

The Net Zero 2050 Mitigation Agenda is vast. It engages virtually every sector of society, the global economy, and the world's natural ecosystems. It will require the transformation of every aspect of modern life on Earth: energy, transport, buildings, manufacturing, agriculture, urban planning, natural conservation. The Mitigation Agenda is classed in two broad categories: (1) reduction of emissions; and (2) Carbon Dioxide Removal (CDR) from the Earth's atmosphere of CO2 that has already (and will be) emitted. The climate change Adaptation Agenda is no less challenging, framing worldwide efforts to adapt to coastal and inland flooding, drought, wildfire, heat, famine, storms. The Adaptation Agenda encompasses food, water, cities, infrastructure, disaster risk management and the natural environment.

This paper focuses on those elements of the Net Zero 2050 Mitigation and Adaptation Agendas most closely aligned with the Lincoln Institute's resources, expertise and capacity in land policy.

We note throughout the paper where discussion of important elements of these agendas are not reviewed because they do not align with LILP's mission and expertise. Examples of emissions technologies excluded from this paper include nuclear and hydroelectric power. Similarly, emission reduction technologies tied to specific economic sectors are excluded: manufacturing, development of electric vehicles, demand management through energy efficiency measures and behaviors. CDR technological solutions such as Direct Air Carbon Capture and Storage (DACCS), enhanced weathering and biochar are likewise excluded.

Other critical emissions reduction Mitigation measures which may align with Lincoln's portfolio are briefly reviewed, given their importance to land use policy, but are deferred for thorough investigation. Examples include the energy efficiency retrofit of buildings, the transformation of the food, agriculture, ranching sectors. Similarly, several CDR measures have profound implications for land use policy (e.g., Bioenergy Carbon Capture and Storage—BECCS), and are briefly reviewed in this paper for further consideration by Lincoln.

The Lincoln Institute is well positioned to help provide critical solutions for the Net Zero 2050 Mitigation Agenda and the climate change Adaptation Agenda. This paper explores those mitigation and adaptation measures where they intersect with land policy and land use, and where they fit well with LILP's expertise, capacity and resources.

1. LAND POLICY, NET ZERO AND CLIMATE CHANGE

Land policy and land use are both a major contributor to and mitigating influence on global warming. This is true when applied to both the Mitigation and Adaptation agendas. Land is a major source of GHG emissions. Land policy and land use must change to maximize their potential to provide climate change solutions, and to minimize their contributions to emissions. Furthermore, much of the adaptation agenda can only proceed in concert with how land is used, governed, regulated, titled and financed.

The United Nations, the UN Intergovernmental Panel on Climate Change (IPCC), the UN Race to Zero Campaign, the recently concluded UN Conference of the Parties (COP 26) in Glasgow, the European Commission, the International Energy Agency (IEA), and global scientific consensus all conclude that to avoid the most devastating effects of climate change, the world must limit global warming to 1.5° C by 2100 from pre-industrial levels.

To achieve this goal, global GHG emissions must be reduced at an unprecedented pace and scale. GHGs principally include CO2, methane (CH4) and nitrous oxide (N2O). Collectively, these gases are referred to as CO2e (CO2 equivalent), taking into account each individual gases' differing climate warming values. There is widespread agreement within the scientific community that limiting global warming to 1.5° C requires that global GHG emissions must reach "net zero" by the year 2050. The Net Zero 2050 goal is defined as eliminating new net increases in GHG emissions to the atmosphere. It will be achieved through a combination of emissions reductions and CDR measures.

Considerable scientific research has been invested in calculating the amount of CO2 the world can emit while limiting global warming to 1.5° C, under alternative "pathways," or scenarios, to hit the 1.5°C mark. This amount of CO2 emissions is referred to as The Carbon Budget. It represents a key measure against which mitigation strategies should be evaluated and pursued. The IPCC estimates for a "medium" chance of limiting warming to 1.5° C, the global Carbon Budget is 770 GtCO2. A "likely" chance requires limiting global emissions to 570 GtCO2. Variations among the IPCC estimates result from differing assumptions regarding economic activity, population growth, and the scale and pace of global warming.

Annual global CO2 emissions in 2021 are projected to total 36.4 GtCO2. Global emissions declined to 34.8 GtCO2 in 2020 from 36.7 GtCO2 in 2019 due to the economic contractions of COVID. The 2021 growth of 1.6GtCO2 is similar to that observed following the global financial crisis of 2008-2009: 1.7 GtCO2 or 5.5% above 2009 levels.

The Climate Action Tracker (CAT), a collaboration of Climate Analytics and the New Climate Institute, employs the *MAGICC climate model* to quantify countries' Nationally

Determined Contributions (NDCs) to reducing emissions against their actual emissions, measured against the Carbon Budget. Countries' National Adaptation Plans (NAPs) attempt to identify, quantify, prioritize and cost measures to adapt to the effects of climate change. NDCs and NAPs are used to quantify the adequacy of a country's efforts to mitigate emissions and adapt to the effects of climate change.

CAT and others, measuring pledges from the Glasgow COP (Conference of the Parties) 26, estimate that at the current and projected pace of emissions, the world will exhaust its Carbon Budget for a "likely" chance of limiting warming to 1.5° C by 2030.

Mitigation efforts to reduce emissions, and to achieve Net Zero, must be measured against this Carbon Budget and time frame to determine their materiality, efficacy, and their consistency with the UN's Sustainable Development Goals (SDG) (https://sdgs.un.org/goals) and other goals.

The Network for Greening the Financial System (NGFS) is a group of 91 central banks and supervisors and 14 observers committed to sharing best practices, high quality modeling of risk management in the global financial sector, and to mobilizing global financial support for transitioning to a sustainable world economy. NGFS has created a model to measure alternative scenarios for the transition to net zero 2050. It is the product of collaboration among NGFS with the Potsdam Institute for Climate Impact Research (PIK), the International Institute for Applied Systems Analysis (IIASA), the University of Maryland (UMD), Climate Analytics (CA), the Swiss Federal Institute of Technology in Zurich (ETHZ) and the National Institute of Economic and Social Research (NIESR).

The NGFS Model embraces the uncertainty inherent in scenario modeling. It posits six scenarios across a range of transition outcomes: "orderly" to "disorderly" to "hot house world" scenarios. These scenarios measure transition risks, physical risks and economic impacts in a 2100 world that ranges between 1.5° to 3.0°C+ hotter than pre-industrial levels. NGFS Scenarios are used by a number of analysts to estimate, or hypothesize, economic impact, capital requirements, job creation and loss, risk of stranded physical assets and other outcomes of the transition to Net Zero 2050. For example, the McKinsey Global Institute's January 2022 report *The Net-Zero Transition: What It Would Cost, What It Could Bring* is predicated on the NGFS relatively orderly transition scenario to 1.5°C.

GHG emissions, since the 2001 Greenhouse Gas Protocol (revised) published by the World Business Council for Sustainable Development and the World Resources Institute (WRI), have been classed into three categories: Scope 1, 2 and 3. These may be summarized in the following chart:

Scope 1	Scope 2	Scope 3
Fuel combustion Company vehicles Fugitive emissions	Purchased electricity, heat and steam	Purchased goods and services Business travel Employee commuting, Waste disposal Use of sold products Transportation and distribution (up- and downstream) Investments Leased assets and franchises

Source: Carbon Trust

Scope 1, 2 and 3 categorizes how a company or enterprise, including nonprofit and state enterprise, generates emissions from its operations, both directly and indirectly throughout its value chain. Scope 1 and 2 emissions fall most directly within an organization's direct control. Scope 2 emissions may be most directly eliminated by relying increasingly (and ultimately, exclusively) on renewable energy sources. Scope 3 emissions comprise the large majority of most organizations' emissions, and may be most difficult to control. For example, the embodied energy in products manufactured by a company's suppliers may, or may not be, influenced by the company ordering the material.

To be credible, Net Zero aspirations of organizations, and nations, must account for, address and provide verifiable, quantifiable mitigation of GHG emissions across all three Scopes, but most particularly Scope 3.

1.1. Mitigation Agenda

Achieving Net Zero 2050 will require global mitigation efforts to simultaneously reduce new emissions and remove GHGs (principally CO_2, but importantly including methane and nitrous oxide) which currently exist in the Earth's atmosphere. Reducing emissions will require wholesale reduction, if not elimination, of fossil fuels from five major sectors of the global economy: energy, transport, manufacturing, buildings and agriculture. Removing existing GHGs from the Earth's atmosphere will require both land-based, or nature-based (NBS), and technological solutions.

The IEA reports that the energy sector is the source of approximately 75% of global GHG emissions. The IEA's Roadmap (described below) for the global energy sector charts a course to achieve Net Zero emissions by 2050.

However, even if fully realized, the IEA's Roadmap to Net Zero will leave the world with increasing GHG emissions, caused by the destruction of carbon-absorbing forests, peat lands, savannahs, by depleted soil conditions, by tundra thaw, and by GHG-emitting farming and ranching practices. The IPCC reports that agriculture, forestry and other land uses (AFOLU) account for 13% of CO2, 44% of methane and 81% of nitrous oxide emissions. Collectively, AFOLU GHG emissions represent 23% of total net anthropogenic emissions.

Moreover, the removal of existing high levels of CO2 in the atmosphere will rely overwhelmingly on land management policies and practices: reduction of deforestation, reforestation and afforestation, soil carbon practices, bioenergy with carbon capture and storage (BECCS), biochar and enhanced weathering. In some analyses, the land sector can contribute about 30%, or 15 GtCO2e (CO2 equivalent) per year, of the global mitigation needed to meet the 1.5° target.

Collectively, reducing emissions and removing GHG from the atmosphere is referred to as the Mitigation Agenda.

1.2. Adaptation Agenda

Concurrently, sufficient global warming is baked into the Earth's climate to all but assure devastating impacts: polar ice melt, sea level rise, drought, heat waves, wildfires, hurricanes, storms and floods, food and water insecurity for tens, if not hundreds of millions of people. Widespread coastal and inland flooding, famine and climate-caused migration on a historically unprecedented scale are all but unavoidable. Some impacts are now categorized as irreversible. These impacts will vary widely by the degree and pace of global warming, and by geography, population growth and migration.

The Global Commission on Adaptation posits a grim litany of climate change impacts:

- Growth in global agriculture yields may be depressed by 30% by 2050, with 500 million small farms most affected;
- The number of people who may lack adequate water at least one month per year will increase from 3.6 billion to 5 billion by 2050, half the world's projected population;

- Rising seas and storm surges could force hundreds of millions of coastal residents from their homes by 2050; and
- Climate change could place more than 100 million people in developing countries below the poverty line. (GCA: Adapt Now, September, 2019)

To confront these impacts, massive governmental, societal and economic adaptation measures at international, national, regional and local levels must be mounted simultaneously. Global consensus on the definition, specification and cost of adaptation measures is less well developed than for many mitigation measures. The adaptation literature from the UN and affiliated entities tends to focus on cases, and on themes. These themes, as framed by the Adaptation Action Agenda of the 2021 Climate Adaptation Summit, include: infrastructure, finance, jobs, health, disaster preparation and response, urbanization and mobility, agriculture and food, and water. Examples include: dikes and seawalls; upgraded water, sewer, drainage and storm management infrastructure; rebuilt energy and water distribution grids; wholesale changes to agricultural and ranching practices for food production, distribution, consumption and waste; remaking urban transportation systems and street infrastructure.

Collectively, such measures are referred to as the Adaptation (and/or Resilience) Agenda.

1.3. Equity Agenda

The warming of the planet, and its devastating impacts, result directly from the industrial development of wealthy nations over the last 150 years. Developed industrial economies and states created their wealth as a direct result of burning fossil fuels. Yet the effects of global warming caused by the developed world are disproportionately experienced by poorer, developing nations and their people, who neither caused the problem, benefitted from the wealth created, or have the financial means to protect themselves from the dire effects of climate change. Developing economies have a fraction of the capital resources required for mitigation and adaptation, and are further burdened with numerous other structural barriers to progress. This calls for the developed world to help pay for the mitigation and adaptation required in the developing world.

The climate compensation demands developing nations made on wealthy nations for climate change-induced environmental and economic "loss and damage" become a point of contention at COP 26, with little resolution.

At the 2015 Paris Climate Summit (COP 25), the developed world pledged to provide $100 billion annually to help developing nations fight climate change. That pledge went unfulfilled, with total aid only reaching $80 billion by 2020. These pledges pale in comparison to the estimates of capital needed to pay for adaptation measures alone among developing countries. The UN Environmental Programme, in its Adaptation Gap Report 2021 (cited below), estimates annual adaptation finance needs of developing countries are five to ten times that amount.

The McKinsey Global Institute estimates that capital spending on physical assets for energy and land-use systems in the net zero transition will total $275 trillion from 2020-2050 (based on the NGFS relatively orderly transition scenario to 1.5°C cited above). This represents an increase of $3.5 trillion in annual spending above current levels (about $5.7 trillion per year). McKinsey's estimate is based on one "orderly" pathway to 1.5°C using the Net Zero 2050 scenario from the Network for Greening the Financial System (NGFS).

There were some hopeful signs at Glasgow:

- An $8.5 billion commitment from the US, the UK, France, Germany and EU to South Africa to help pay for its energy transition from coal to renewables;
- A $2.8 million pledge by Scotland to address "structural inequalities".
- A $1.5 billion pledge by twelve international donors over the next four years to support protection and sustainable management of the vitally important Congo Basin forests and peatlands. While regional experts welcomed the news, all agree that $1.5 billion is far from enough to preserve the Congo peatlands and forests in an equitable manner, respecting indigenous land rights, and providing economic support for the people of the region.

Such commitments represent the merest fraction of 1 percent of the capital required to mitigate emissions and adapt to climate change within developing and emerging economies, given the estimates from McKinsey and NGFS noted above. The Glasgow communique failed to resolve these loss and damage claims, or provide pledges at the meaningful scale needed to meet them.

The Climate Change Equity Agenda, framing and meeting the needs of developing and emerging countries and their residents, is crucial to achieving Net Zero 2050. Just as importantly, the Equity Agenda constitutes an economic, political and social imperative to safeguard vulnerable populations and nations. The Equity Agenda—quantifying, financing, implementing it—is beyond the scope of this paper. Nevertheless, it remains a central concern of LILP, a requirement of a just and effective transition, and should be elucidated in subsequent work.

This Loss and Damage agenda will require large scale capital investment for developing countries to both mitigate, and adapt to the effects of, climate change. Without such assistance, achieving Net Zero 2050 will prove elusive, if not impossible.

2. LAND AND THE MITIGATION AGENDA: REDUCING AND REMOVING GHG EMISSIONS

Net Zero 2050 cannot be achieved without maximizing clearly articulated land-based solutions. These have been highlighted, and prioritized according to their efficacy, by the IPCC in its 2019 Special Report: Climate Change and Land (subtitled: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems.)

The IPCC reports that AFOLU account for one third of gross global GHG emissions. The Special Report focuses on five principal land-based solutions to mitigate GHG emissions:

- Preservation of existing forests, peatlands and grasslands, Reforestation, Afforestation;
- Soil Carbon Sequestration in Croplands and Grasslands;
- Bio-Energy with Carbon Capture and Storage (BECSS);
- Biochar; and
- Enhanced Weathering.

The World Resources Institute (WRI) summarizes seven key conclusions from the IPCC Special Report on Climate Change and Land:

> "1. The way we're using land is worsening climate change.
>
> 2. But at the same time, land acts as a tremendous carbon sink.
>
> 3. The very land we depend on to stabilize the climate is getting slammed by climate change.
>
> 4. Several land-based climate solutions can reduce emissions and/or remove carbon from the atmosphere.
>
> 5. Many land-based climate solutions have significant benefits beyond curbing climate change.
>
> 6. Some land-based climate solutions carry significant risks and trade-offs, and need to be pursued prudently.
>
> 7. In particular, land-based climate solutions that require large land areas could threaten food security and exacerbate environmental problems."

The speed and scale with which land policy and land use must change to maximize their potential to mitigate global warming call for urgent realignment of how governments at every level, along with the private sector, use land. A number of land use solutions that mitigate emissions conflict with many of the UN's Sustainable Development Goals (SDGs) (particularly around food security, water management and biodiversity.

Roe et al in the journal Nature (October 2019), "Contribution of the Land Sector to a 1.5°C World," reviewed modelled pathways and literature of the land sector and its potential contribution to Net Zero 2050. They developed a roadmap for a number of priority land-based measures and geographic regions through 2050 to maximize their mitigation outcomes for a 1.5° C world. This roadmap seeks to ensure co-benefits with the goals of biodiversity, water, air, soil, resilience, food security and livelihoods. Further, the roadmap seeks to advance other key international goals, such as the UN's SDGs, the UN Convention on Biological Diversity, the New York Declaration on Forests (NYDF) and others. Finally, it seeks to minimize adverse impacts of some land-based solutions.

The authors conclude:

> "Transforming the land sector and deploying measures in agriculture, forestry, wetlands and bioenergy could feasibly and sustainably contribute about 30%, or 15 billion tons of carbon dioxide equivalent ($GtCO_2e$) per year, of the global mitigation needed in 2050 to deliver on the 1.5 °C target."

The climate change mitigation agenda for land policy and land use must be developed as a portfolio of solutions, with care to maximize mitigation outcomes, complement the SDGs and provide important co-benefits with other key international agreements, while simultaneously minimizing adverse impacts. This will require an assessment of both (1) nature-based solutions (NBS), e.g., prevention of forest deforestation, reforestation and soil carbon land management practices; and (2) technology solutions, e.g., BECCS, biochar, enhanced weathering, direct air capture (DAC).

The IPCC report on Land and Roe's research do not consider the effect of urban form on global emissions. The World Economic Forum (WEF) report on Urban Transformation: Integrated Solutions (September, 2021) frames a proposed agenda for the role of urbanization in limiting GHG emissions. Much of this urbanization/emissions agenda focuses on green energy and energy efficiency, not on urban form. Central policies identified by the WEF include:

- green building standards;
- low-cost green financing;

- green urban energy infrastructure;
- decarbonizing public vehicle fleets and emphasizing mass transit;
- urban systems for a circular economy: waste treatment, recycling and reuse; and only finally
- compact urban form and planning.

Galina Churkina's research regarding urbanization and the global carbon cycle (January 2016) posits the notion of urban carbon "sinks," processes, activities or mechanisms in the urban ecosystem which remove GHGs from the atmosphere.

Churkina further explores the possibility that engineered timber for midrise building construction required for a massive wave of urbanization in the next 30 years may reduce GHG emissions from the manufacture of steel, cement and other building materials (*Nature Sustainability*, 2020).

Muniz and Dominguez' literature review of urban form, spatial structure and per capita carbon emissions in large US metropolitan areas (*Sustainability*, 2020) exemplifies work which attempts to define, if not quantify, the impact of urban development (and associated land policy) on GHG emissions.

Urban form and land policy will prove central to adaptation measures as well.

We discuss urban form and the Mitigation and Adaptation agendas in a separate section of this paper below.

2.1. Reducing GHG Emissions by Sector

The path to Net Zero emissions is guided by the source of emissions by economic sector. Different sectors of global economic activity have disproportionate impact on emissions. Broadly speaking, these sectors are identified as Energy, Agriculture, Forestry and Land Use (AFOLU), Industry, Transport, Buildings and Waste. A number of scientific and international organizations monitor GHG emissions globally, and sectoral contributions to emissions. The immediate and grave threat climate change poses for human society and ecosystems globally requires a comprehensive roadmap to achieving net zero emissions. Such a roadmap will account for the differing contributions to global emissions by sector.

In recent years, global emissions totaled 36.7 GtCO2e in 2019, 34.4 GtCO2e in 2020 (representing a 5.4% decline caused by COVID-related economic contraction), followed by a quick rebound of 4.9% to 36.4 GtCO2e in 2021 (The Global Carbon Project, GCP, and Carbon Brief).

The Climate Watch project of the World Resources Institute (WRI) regularly monitors GHG emissions by sector. WRI reported that for the year 2016, the Energy sector accounted for 73.2% of global GHG emissions, AFOLU 18.4%, followed by Industry at 5.2% and Waste at 3.2%. However, this oversimplified allocation of GHG emissions to sector masks a more complex map. Within the Energy sector as a whole (73.2%), energy use in Industry accounts for 24.2%, Transport for 16.2%, and Buildings for 17.5%. The balance of Energy sector emissions derive from fugitive emissions from energy production (5.8%) and unallocated fuel combustion (7.8%).

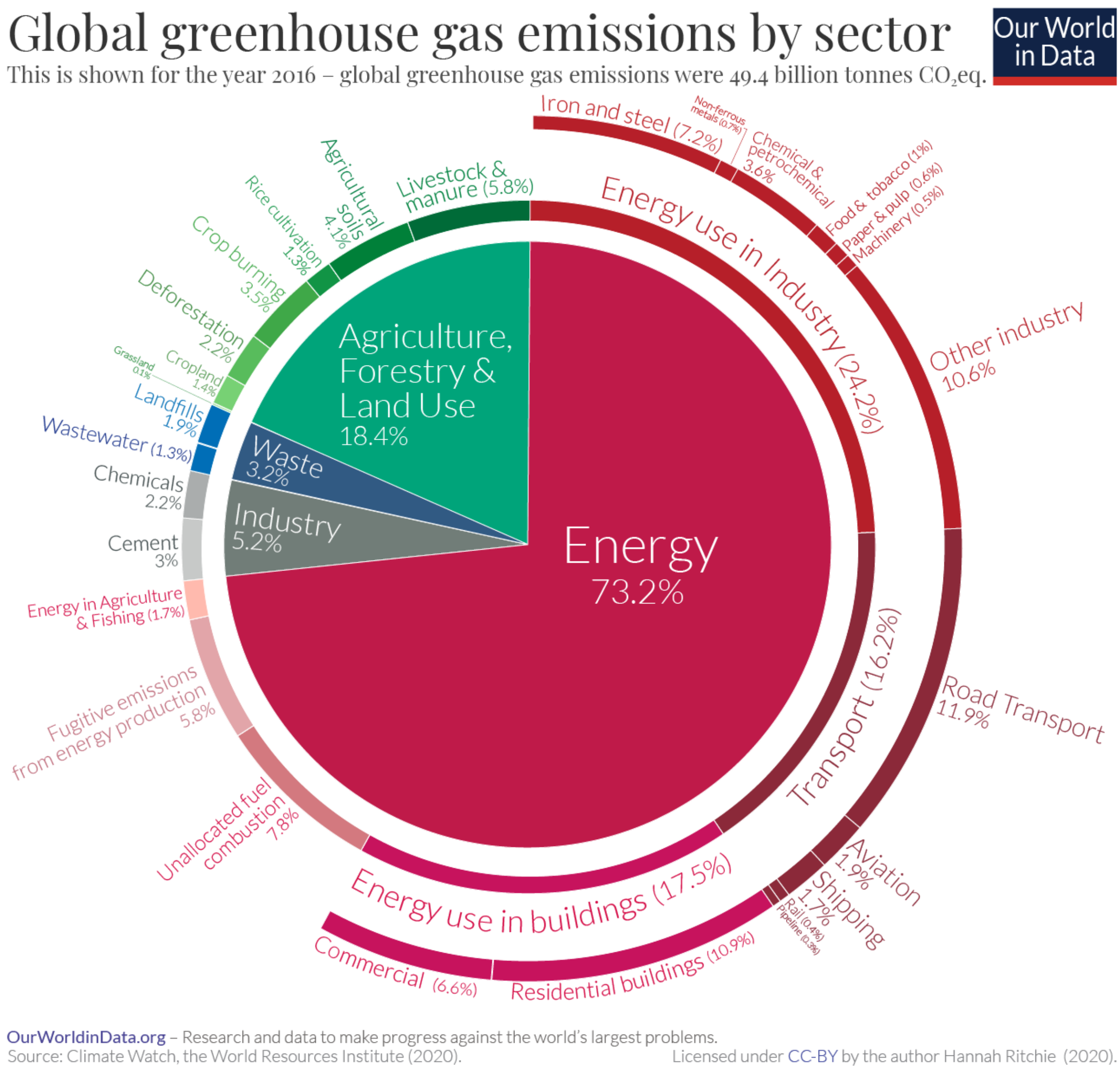
There are further nuances in Energy sector emissions:

- Buildings: 6.6% commercial; 10.9% residential;
- Transport: 11.9% road; 1.9% aviation; 1.7% shipping; and
- Industry: 7.2% iron and steel; 10.6% other industry; 3.6% chemicals;

Or AFOLU emissions:

- Livestock: 5.8%;
- Agricultural soils: 4.1%
- Crop burning: 3.5%;
- Deforestation: 2.2%

WRI's pie chart below gives a more complete picture, keeping in mind these percentages will vary by country and region.



All visualizations, data, and code produced by Our World in Data are completely open access under the [Creative Commons BY license](). You have the permission to use, distribute, and reproduce these in any medium, provided the source and authors are credited. The data produced by third parties and made available by Our World in Data is subject to the license terms from the original third-party authors. Hannah Ritchie and Max Roser (2020) - "CO_2 and Greenhouse Gas Emissions". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions' [Online Resource]

Plainly, the Energy sector collectively accounts for the large majority of global GHG emissions. Any roadmap to Net Zero 2050 must detail the decarbonization of the entire energy sector. In their report Net Zero by 2050: A Roadmap for the Global Energy Sector (May, 2021), the International Energy Agency (IEA) notes:

> "The energy sector is the source of around three-quarters of GHG emissions today and holds the key to averting the worst effects of climate change, perhaps the greatest challenge humankind has faced. (The Net Zero 2050 Agenda) calls for nothing less than a complete transformation of how we produce, transport and consume energy.
>
> "The number of countries that have pledged to achieve net zero emissions…now covers around 70% of global emissions of CO2…Most pledges are not yet underpinned by near-term policies…Even if successfully fulfilled, (current) pledges would still leave around 22 GtCO2 emissions worldwide in 2050….consistent with a temperature rise in 2100 of around 2.1°C. Further delay in acting to reverse that trend will put net zero by 2050 out of reach."

The IEA Roadmap to Net Zero 2050 specifies the following goals:

- Renewables reach nearly 90% of total electricity generation;
- Solar PV and wind reach nearly 70% of total electricity generation;
- Hydrogen-related fuels reach 10 of total final consumption of energy;
- About 90% of production in heavy industries is low-emissions;
- Electric vehicle (EV) car sales go from 5% to more than 60% by 2030;
- No new sales of fossil fuel boilers;
- No new unabated coal plants approved for development;
- No new oil and gas fields approved for development;
- No new coal mines or mine extensions;
- Provide electricity to 785 million people with no access; and
- Provide clean cooking solutions to 2.6 billion people.

The IEA Roadmap is based on an economic/demographic model which projects global energy demand in 2050 is about 8% smaller than today, but serves an economy with global GDP twice the size of today's ($95 trillion in 2021), with a population of 2 billion more people. Total energy supply overwhelmingly comes derives from renewable sources: two-thirds of energy generation in 2050 is projected to come from solar, wind, bioenergy, geothermal and hydropower. Solar becomes the largest source of energy generation, representing a 20-fold increase over today's capacity by 2050. Wind power grows 11-fold over today's production.

Today, fossil fuels account for approximately 80% of world energy supply. The IEA Roadmap calls for this to decline to 20% by 2050. IEA calls for no new investment in coal mines or existing coal mine extensions. Nor is there any new development of oil and gas fields.

Electricity will account for half of the world's total energy consumption in 2050, driven by an increasing role in all sectors—transport to buildings to industry—and will prove essential to develop biofuels such as hydrogen.

Annual global investment in energy will sharply rise if these goals are to be met between today and 2050. McKinsey estimates that $1 trillion per year will be required for energy generation; $820 billion per year for grid improvements and $120 billion per year for energy storage; or nearly $60 trillion through 2050. Another estimated $3.5 trillion per year in EV development and charging infrastructure, $1.7 trillion per year in building energy efficiency and additional investments in agriculture, food, forestry and land use bring total estimated spending through 2050 to around $220 trillion.

IEA, in their Net Zero 2050 Roadmap, projects total global annual energy investment rises to $5 trillion by 2030, up sharply from its current estimate for 2021 of $1.9T. Together with the IMF, IEA estimates this additional energy investment will raise global GDP by 0.4% per year, or 4% higher in 2030 than it would be based on current trends.

Emissions from industry, transport and buildings are harder to achieve, will take longer, and will require development and investment in technologies that today are only in R&D, prototype or initial deployment phase.

Land Policy, the Clean Energy Transition, and LILP Focus

As noted in the Preface, this paper's discussion of the nexus between land policy and reducing GHG emissions will be limited to those areas which most closely match LILP expertise, capacity and resources.

Due to their implications for land use, elements of the Energy sector reviewed below include solar photovoltaic (PV), new transmission corridor infrastructure, and biofuels). Excluded from the energy sector discussion in this paper are the following technologies: nuclear energy, hydroelectric energy, wind, hydrogen-powered sources, battery storage, energy efficiency improvements in appliances, heating and cooling systems. Wind energy and hydroelectric power in particular involve large land areas in the energy transition, and constitute significant tradeoffs in land use. Also excluded are critically important reductions in energy demand through efficiency measures and changes in consumer, industry and agriculture behavior.

These energy sectors may be explored by Lincoln in subsequent inquiry.

Transport

The largest transition required of the Transport sector is the development, manufacture and sale of EVs. This technological and manufacturing development falls outside LILP's remit. Decarbonizing urban mass transit is a critical component of EV development, but again outside LILP's practice. Further, the deployment of widespread, ultimately universal, access to EV charging networks (whether urban, suburban or rural) will be required along with the manufacture and sale of EVs. And urban street infrastructure likely must change to better accommodate EVs, their charging, parking and storage infrastructure. While these too represent important elements of urban policy, they fall outside LILP's focus on land policy. It is possible that urban infrastructure planning, development, finance and investment required to accommodate EVs for both mass transit and personal transport may represent a field of subsequent inquiry for Lincoln.

Other aspects of decarbonizing the transport sector fall outside of Lincoln's purview: aviation, shipping, rail, long-haul trucking.

Buildings

Similarly, the Buildings sector constitutes a key element to achieving Net Zero emissions by 2050. The path to net zero building emissions includes energy efficiency and renewable energy (EERE) retrofits of existing buildings and their appliances/infrastructure, the electrification of the Buildings sector, and the adoption of net zero building standards for new development.

Energy efficiency improvements and electrification across all economic sectors—in addition to the Energy sector—will be required at massive scale to help achieve Net Zero 2050. The Global Commission for Urgent Action on Energy Efficiency published its recommendations in 2020. The European Union has published its own 2030 energy efficiency targets, carrying out its July 2021 proposed revision to the longstanding EU's Energy Efficiency Directive.

In the United States state building codes increasingly require tighter energy efficiency standards for new construction. Mortgage lenders are moving to value energy efficient mortgages as an incentive to retrofit existing homes and buildings. State utility regulators are establishing energy efficiency portfolio standards as requirements for utilities to promote energy efficiency retrofits. McKinsey's Transition report, drawing upon a pathway to Net Zero modeled by the NGFS, calls for $1.7 trillion in energy efficiency investments in existing buildings. This figure pales in comparison to total investment in energy efficiency for the period 2015 to 2050 projected by the International Renewable Energy Agency (IRENA) in its pathway to net zero: $53 trillion, averaging $1.5 trillion per year. (This compares to

IRENA's estimate of the "Reference Case" for projected energy efficiency spending based on current trends of $29 trillion, an 83% increase.)

While not explicitly a matter of land policy, EERE retrofit, electrification and net zero new construction standards remain a policy area of interest to the Lincoln Institute and may be reviewed in subsequent research and practice. Energy efficiency advances in design, engineering, appliances, insulation, heating and cooling, cooking, lighting and consumer behavior in buildings will prove critical to reduce energy demand. Again, discussion of this important agenda falls outside this inquiry for LILP, and may be taken up in a subsequent effort.

Manufacturing

The Manufacturing sector (contributing, for example, 23% of GHG emissions in the US in 2019 according to the US EPA) constitutes another significant sector generating GHGs. Again, the technologies required to decarbonize manufacturing fall outside Lincoln's purview. Accordingly, they are not discussed in this paper.

2.1.1. Solar Energy

The transition to Net Zero 2050 will require a rapid, massive acceleration in the deployment of solar PV energy generation. The IEA calculates that 630 GW of solar generating capacity must be constructed annually through 2050, representing an increase of 18,900 GW of solar generation above current levels. This compares to a mere 580.1 GW of installed solar generation capacity as of 2019, plus an additional 3.4 GW in off-grid generation, according to the International Renewable Energy Agency (IRENA). This represents a 32-fold increase over current capacity.

In 2020 IEA estimated the cost of installed utility-scale solar projects at $30-60/MWh in Europe and the United States, and $20-$40/MWh in India and China where "revenue support" instruments such as guaranteed price supports are in place, combined with low cost financing and high quality (solar value) resources. IEA notes that for "projects with low-cost financing that tap high-quality resources, solar PV is now the cheapest source of electricity in history."

In the Fall of 2021, the Lawrence Berkeley Lab reported, measuring in MW (rather than MWh) that median installed costs of PV fell by 74% (or 12% annually) since 2010, to $1.42/Wac ($1.05/Wdc) in 2020. (Some energy is lost in that conversion–generally between 15% to 20%. So, a solar farm with a capacity of 100 MW of direct current (100 MWdc) generates roughly 80-85 MWac.) Costs vary whether systems are tracking (following the sun) or not, as well as grid interconnection costs and proximity, land costs, set-backs and the addition of storage.

Solar PV costs vary across continents. Based on the above cost estimates for the US, current installation costs, inclusive of trackers and ready grid interconnection may be estimated at $1.0 million per MW. Thus, 3,200 MW, converted to alternating current, will cost approximately $4 trillion. It is important to remember that these costs are not static, and do not take into account incentives, subsidies or the value of energy sales (e.g., power purchase agreements and other mechanisms.) The cost of land will vary widely. Materials cost may increase with scarcity, or may be contained by recycling older panels and materials. Technology will advance productivity, longevity, installation methods, and lower operating and replacement costs. These costs do not include the cost of land, battery storage, or the cost of new transmission lines and capacity.

Utility scale solar PV (along with other energy sources) will require large amounts of land. Princeton University, using data from the US Departments of Energy, Interior and Agriculture, and the Nuclear Regulatory Commission, reported in June 2021 that total installed solar PV capacity in the United States covered 500,000 acres of land. Acreage requirements in the US for solar, like costs, have fallen, from 7300 acres per GW 2013-2017 down to 3700 acres per GW from 2018-2020.

The Princeton study examined the relative consumption of land for different energy sectors in the United States. The comparison provides a rough guide to land use demands for different energy sources, which may be extrapolated, with caution, to installations worldwide. Princeton reported that of 81 million acres in the US used for energy, (roughly the size of Missouri and Iowa):

- Biofuels consumed by far the largest amount of land, 51.5 million acres (more than the entire state of Missouri), but only produced 5% of the nation's energy, the most inefficient use of land for energy of all sources. (Biofuels and their land requirements, energy production, and adverse impacts on land for food production and water consumption are discussed below.
- Hydropower used 8.7 million acres;
- Wind farms (total footprint) used 6.7 million acres, though the turbines themselves took very little land (70,000 acres);
- Power lines used 4.8 million acres;
- Natural gas systems used 4.4 million acres;
- Coal 0.6 million;
- Nuclear 0.23 million; and
- power plants 0.15 million acres.

These land use requirements for various energy generation technologies, compared to amount of energy produced, and relative capital and operating costs, provide a valuable comparison with which to examine the alternative pathways to Net Zero 2050 modeled by agencies such as IEA, IRENA, Princeton, US Department of Energy, the EU, McKinsey, and others.

Using the Princeton values for the land requirements of solar may require adjustment for:

- Differing land requirements, solar gain maps, access to grid distribution and storage;
- Variations in land requirements for small scale community solar and distributed systems, such as have been deployed in India and developing countries; and
- Rooftop solar, which requires no additional land.

Princeton's Net-Zero America Project maps various land use requirements for the United States carbon-free energy future. Under the Princeton scenario with wind and solar providing 98% of the nation's energy needs, and with the elimination of fossil fuels and nuclear power, land requirements quadruple in size. Wind farms occupy 250 million acres, the size of Arkansas, Iowa, Kansas, Missouri, Nebraska and Oklahoma.

While certainly sizeable, these land requirements for renewable energy generation may be managed within the US. By comparison, the contiguous United States comprise 654 million acres of ranchland and 391 million acres of farmland, potentially compatible with dual use for wind farms. Ranchers and farmers collected $820 million in energy lease payments in 2020. Recent demonstration projects have suggested the viability of growing corn productively, with less water, underneath solar panels providing shade.

Nevertheless, the land requirements for solar, based on the Princeton findings, provide an order of magnitude scale to inform land use decisions globally. IEA's call for 18,900 GW of new solar worldwide to achieve its Net Zero 2050, again using the Princeton values ranging from 2013-2020, will require from 108,000 to 216,000 square miles, or 280,000 to 560,000 square kilometers. Rooftop solar will likely prove inadequate in high density urban communities of developing nations, whether existing or planned for increasing urbanization. Community solar, micro grids, and very small scale solar generation for rural communities in developing nations will likely require much less land, and less capital. The IEA Roadmap calls for rooftop solar installations to surge from 25 million in 2020 to 240 million globally in 2050.

The location of (very) large scale new solar PV generation facilities serving high density urban populations will likely require substantial investment and land in grid, storage and distribution infrastructure. If required for forested land for sequestration, this demand will entail significant tradeoffs. Mini grids and community solar networks may lower this demand for land substantially in rural areas.

Similar analysis may be done for the United States. The US Department of Energy in the Fall of 2021 published the Solar Futures Study. It shows the feasibility of solar's contribution to decarbonizing the US energy grid by 2035 (as President Biden has proposed), and by 2050, under two alternative scenarios. The first scenario ("Decarb") decarbonizes the grid sufficient to serve current case electricity usage. The second scenario ("Decarb+E") intensifies electrification of the transport, building and industry sectors, and for production of clean fuels such as hydrogen via electrolysis.

Under US DOE's Decarb+E scenario, an additional 3,200 GW of solar is developed by 2050. For comparison, at the end of 2020, the US had 97.3 GW of installed solar generation, two thirds of which was utility scale, and one third small scale distributed solar, largely via rooftop installations. DOE's scenario calls for a 32-fold increase in solar generation capacity in the US by 2050.

The acreage requirements for these systems are substantial, but manageable. Using Princeton's values, 3,200 GW will require 11.8 million acres, or 18,000 square miles (roughly the combined size of New Hampshire and Vermont). This may be cut by one third (to 12,000 square miles), if the current proportion of utility-scale to rooftop solar in the US holds. More precise modelling is required to better understand solar land requirements when taking into account utility scale, rooftop solar, and community solar installations.

DOE (op cit) comments on land requirements for this level of solar development:

> Although land acquisition poses challenges, land availability does not constrain solar deployment in the decarbonization scenarios. In 2050, ground-based solar technologies require a maximum land area equivalent to 0.5% of the contiguous US surface area. This requirement could be met in numerous ways including use of disturbed lands. The maximum solar land area required is equivalent to less than 10% of pentanal suitable disturbed lands, thus avoiding conflicts with high-value lands in current use. Various approaches are available to mitigate local impacts or even enhance the value of land that hosts solar systems. Installing PV systems on waterbodies, in farming or grazing areas, and in ways that enhance pollinator habitats are potential ways to enhance solar energy production while providing benefits such as lower water evaporation rates and higher agricultural yields.

The most difficult land-use challenge for the development of solar, or any, green energy system, will likely be building transmission lines. The foregoing discussion of the scale, estimated capital cost and land use requirements to develop the solar PV generation capacity required for a Net Zero 2050 pathway does not include a discussion of distribution. A major constraint on development of solar energy assets is the inability of the grid to service these assets. There are many reasons for this. Current grid capacity cannot accept additional load. Land acquisition, rights of way, permitting, zoning and local, state and national policy may restrict, or render impossible, the development of new distribution grid capacity. Utilities will not, or cannot, invest in new distribution lines. Neighborhood opposition to power lines may require undergrounding them, rendering them too expensive to build.

In 2011 former President Obama created the Rapid Response Team for Transmission in an effort to speed the permitting of five transmission lines in the western United States. Only one is under construction. Three face permitting delays, and the fifth was canceled. The Princeton land use study for Net Zero 2050 found that transmission line capacity would need to more than triple under the high-renewable scenario. Under this estimate, and with a reported 4.8 million acres devoted to transmission lines currently in the US, new land required for transmission will exceed 14 million acres. Without transmission interconnection, new solar and wind projects would be stranded, rendering them worthless.

Reviewing the costs of required transmission lines, or of battery storage, for renewable energy generation assets is beyond the scope of this paper. These costs may exceed those of solar PV facilities themselves.

2.1.2. Biofuels: A Vexing Land-Water-Food-Energy Nexus

The IEA Roadmap to Net Zero 2050 envisions an important role for "modern and sustainable" forms of biofuels. IEA highlights the benefits of such biofuels technologies to reduce GHG emissions from sectors difficult to decarbonize: aviation, heavy shipping, types of industry. Further, modern biofuel technologies can often address the energy needs of emerging economies with little to no grid access by offering low-cost, deployable sources of energy.

Traditional burning of solid biomass (e.g., foraged wood, animal waste) for indoor cooking is inefficient, linked to deforestation, a source of indoor air pollution, and according to the IEA the cause of an estimated 2.5 million premature deaths worldwide each year. SDSN and FEEM, cited below, report the figure is 1.6 million, primarily among women and children, caused by 2.8 billion people who burn wood and agricultural and animal waste for fuel. In the IEA NZE Scenario, traditional burning of biomass—which IEA estimates at 40% of current total bioenergy supply, or approximately 25 exajoules (EJ)—falls to zero by 2030.

IEA notes that a shift to modern biofuel methods can avoid placing undue labor on women often burdened with wood gathering for fuel. It will bring large scale health benefits with improved indoor air quality and waste management practices, and reduce methane emissions caused by inefficient combustion and waste decomposition. Further, modern biofuel technology can become an important source of employment and income for poor rural communities in emerging economies.

There exists longstanding awareness that the reliance on biofuels for energy results in competition for land, water, and food. Furthermore, current ("first generation") biofuel practices exacerbate, rather than entirely abate GHG emissions. By converting pasture and range lands to biofuel crops, the practice results in clearing forestlands to create new pastures. The resulting deforestation occurs at material costs to the carbon sequestration benefits of forestland, and other carbon sink lands. Water demands for biofuel crops place increasing pressure on already crisis-level water supplies for billions of people who suffer from water scarcity now. And biofuel production can result in displacement of tens of millions of small scale and subsistence farmers, replacing them with large scale commercial agricultural operations. This often occurs through the expropriation—without compensation—of cooperatively owned or managed land, risks loss of traditional ecological land management expertise, and threatens exploitation and dispossession.

Commercial scale agricultural production of biofuels often accompanies societal effects of large scale agriculture generally:

- Commodification of agriculture;
- Industrialization of agriculture;
- Labor market impacts and labor relations;
- Reconfiguration of property and access;
- Dispossession of commonly held property;
- Violence, repression and coercion.

Dell'Angelo et al, 2017, and forthcoming; De Schutter, 2011; Fuys et al, 2008; Wily, 2011; Cotula, 2012,

Finally, widespread biofuel crop practices damage biodiversity. Numerous studies document the widespread deforestation and large carbon emissions resulting from the palm oil industry in Indonesia and Malaysia, largely for European import. As a response, the European Union's renewable energy mandate does not accept biofuels produced form feedstocks grown on land with "high biodiversity value" (including primary forests, peatlands, wetlands, certain woodlands and grassland). Brazil's biofuel (and ranching) industries have resulted in the destruction of more than 270,000 square miles of rain forest since 1970, an area the size of Texas.

These conflicts with land, food, water, employment and social economies were studied in a 2020 workshop of land-use, water, energy and biofuel technology scientists, engineers and professionals from around the world. Sponsored by the Sustainable Development Solutions Network (SDSN) and the Fondazione Eni Enrico Mattei (FEEM), the workshop produced its report in November 2021: Roadmap to 2050: The Land-Water-Energy Nexus of Biofuels along with the Zero Emissions Solutions Conference (ZESC). At times the Report paints a stark trade-off between biofuel and food production. Brown finds in his 2012 book, *Full Planet, Empty Plates*, that the fuel that fills a regular car tank could feed one person for one year. In terms of calories, SDSN/FEEM report that 200 million people could be fed with crops used for bioethanol, and another 70-80 million people with biodiesel production. Yet even this statistic contrasts with the potentially positive effects of bioenergy investments in crop productivity, increased yields through mechanization, hydraulic infrastructures and technology. (Achterbosch et al, 2013; Burke et all, 2007).

The Report includes a comprehensive literature review of land use, food, water and social conflicts, as well as the GHG emissions tradeoffs of current biofuel practices. It explores the use of modern biofuel technologies ("second" and "third generation") to mitigate the deleterious effects of biofuels, maximize their emissions benefits, and place biofuel energy use in the context of net zero scenarios.

IEA remains sensitive to the land use and food conflicts, and the emissions tradeoffs associated with large scale biofuel practices. IEA does not comment the water conflicts associated with biofuel practices, or on the expropriation of cooperatively-owned lands and the potential to displace millions of small scale and subsistence farmers.

But with these concerns in mind, IEA limits the role of biofuels to those sectors which are difficult to electrify. As noted, these include aviation, heavy shipping, and industries such as cement and paper. In fact, IEA's Roadmap calls for less than half of the median use of biofuels to meet global energy demands in 2050 from the IPCC. IEA notes: "we aimed to ensure that the peak level of total primary bioenergy demand—including losses from the conversion of biomass into useful fuels—falls within the lowest estimates of global sustainably bioenergy potential in 2050." The IEA Net Zero 2050 Roadmap calls for approximately 100 EJ derive from bioenergy sources by 2050, where the median demand from all scenarios modeled by the IPCC called for 200 EJs. In its pathway, the IEA forecasts that of total global bioenergy demand in 2050, approximately:

- 60% is solid bioenergy;

- 30% is liquid biofuels, including energy use for their production; and
- 10% is biogases.

Bioenergy demand is concentrated in those sectors difficult to electrify, or which require low cost locally distributed sources of renewable energy. In 2050, IEA asserts that about 60% of the 100 EJ of global bioenergy supply comes from sustainable waste streams that do not require a dedicated land use. Today, only 20% meets that standard. These waste streams (feedstocks for bioenergy technologies) include organic municipal waste (e.g., district heating infrastructure powered by municipal sanitation in Vancouver, British Columbia), agriculture residues (e.g., onion harvest waste biodigesters in Oxnard, California), and forestry industry residues. The latter provide 20 EJ of bioenergy in 2050 in the NZE scenario. IEA notes this is less than half current "best estimates of (its) total technical potential." Comprehensive collection practices from sustainable waste streams outside of forestry produce another 45 EJ of bioenergy supply, used primarily for biogases and advanced biofuels.

IEA notes that its NZE Scenario of 40 EJ will require land use, compared to 25 EJ from bioenergy crops and forestry practices today. But IEA asserts that in 2050 no bioenergy crops are developed on forested land, and no overall increase in cropland use for bioenergy production will be required.

IEA calls for rotating away from the use of food crops, or "conventional" feedstocks for bioenergy in order to avoid land and food conflicts. The use of such conventional stocks grows through 2030, but then falls below 3 EJ by 2050. This is enabled by a transition to advanced ethanol, advanced biodiesel and biokerosene, in combination with carbon capture and storage technologies, including BECCS technologies (providing 25 EJs). This will require a heavy reliance on short-rotation woody crops grown on cropland, pasture and marginal lands not suited for food production. Another 10 EJs is provided by "sustainably managed forestry plantations and tree plantings integrated with agricultural production via agroforestry…that do not conflict with food production or biodiversity."

IEA's model forecasts that this intensity of land use for bioenergy production will require another 80 million hectares. Of this total, 30 million hectares are new forests, an expansion of global forest area by 1 percent. By 2050, bioenergy production will represent 6 percent of global forest land, identical to today's share. The remaining 50 million hectares are occupied by short-rotation woody crops. Total increase in land use for bioenergy crops rises by 140 million hectares in 2050. IEA asserts that 70 million hectares will be grown on "marginal" lands (that is, lands not suited for crops or pasture), with another 70 million hectares on cropland, "an area the same as today's use of cropland for bioenergy production. IEA's NZE Scenario falls below what it asserts are estimated ranges of land potentially available to minimize conflict with sustainability constraints regarding biodiversity (UN Sustainable Development Goal 15). This is achieved in the IEA Scenario by a drastic curtailment in deforestation.

The Food and Agriculture Organization (FAO) reports that cropland currently covers more than 1.56 billion hectares worldwide. FAO estimates that 34% of the total global land surface is "to some extent" prime land for rainfed agriculture (4.5 billion hectares.) Of this area, 1.56 billion hectares are already in crop production, and 1.8 billion hectares are classed as forest, protected habitat or urban. Accordingly, about 1.2 billion hectares of additional land could be used for crop production. According to these estimates, the IEA projection for additional lands for biofuel production represents about 10% of the remaining cultivatable acreage in the world. This would like require diminution of grasslands, savannahs, pastures and rangeland, providing unique habitat for numerous species of plants and animals. 26 percent of this land is in Latin America; 32 percent in Sub-Saharan Africa, with most of the rest in Europe, Oceania, Canada and the United States. (Souza et al, Bioenergy & Sustainability: Bridging the gaps.)

A primary argument for biofuel production is the reduction of GHG by reducing consumption of fossil fuels. However, biofuel production results in land use change, which in turn reduces the sequestration capacity of existing forestlands, peat lands and others. The lifetime and extent of GHG emissions caused by such land use change may nullify, or at best reduces, the emissions advantage of biofuels over fossil fuels, especially in the medium and long term. (Tilman, et al, 2009) In short, first generation biofuels may generate more GHG emissions that they mitigate without sound management of the agricultural expansion required.

The World Water Assessment Programme estimates irrigation water used for biofuel production in 2014 at 44 km3, or 2 percent of all irrigation water, and that with existing technology, producing one liter of liquid biofuel requires about 2,500 liters of water. ("Fact 22: Water & Biofuels | United Nations Educational, Scientific and Cultural Organization". 2014.Unesco.org.http://www.unesco.org/new/en/natural/sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-22-water-biofuels/). Water use for biofuel varies by region, based on rainfall. In Brazil and Indonesia (sugarcane and palm oil), irrigated water use is negligible. In China and the United States, it is estimated at 2 and 3 percent respectively. SDSN/FEEM reported an estimate that carrying out national biofuel policies in place in 2014 would require 30 million hectares of cropland and 180 km3 of additional irrigation water, almost four times the then current demand for water. (Note that this 2014 estimate for additional cropland is about half that estimated by the IEA for its NZE Scenario, excluding the additional 70 million hectares in marginal lands required for biofuel production. Is SDSN/FEEM's reported water estimate similarly low?

IEA does not directly address GHG emissions from agriculture, forests and other land uses (AFOLU). It does note however that AFOLU accounts for some 5-6 BtCO2e/year. IEA asserts that its emphasis on short-rotation woody crops for biofuel production from marginal and pasture lands would sequester approximately 190 MtCO2e by 2050, reducing AFOLU emission by 140 MtCO2e from today. This represents a mere 2.3% reduction. IEA reports that for CO2 AFOLU emissions to become net negative by 2040 and absorb 1.3 BtCO2e by 2050, deforestation must decrease from current levels by two-thirds, forest management practices must be improved, and another 250 million hectares of new forests must be planted. (The conflict with croplands, food production and water is not addressed.)

Moreover, climate change itself will affect crop yields and arability of land available for biofuel agricultural production. With rising temperatures, unpredictable changes in rainfall and hydrological cycles, biofuel crops may fail, become less productive (and therefore less economic), and may require displacing more, higher value food production crop and pasture lands if biofuels are to meet the IEA targets.

When life-cycle analysis is applied to any energy sector, there will be tradeoffs among costs and benefits. Clearly, biofuels and bioenergy will play an important role in achieving Net Zero 2050. Yet the bioenergy sector is fraught with competing interests and conflicts among land, water, food, energy, biodiversity and social equity interests. With this in mind, a variety of Biofuel Sustainability Certification regimes have emerged in recent years.

Examples include:

- Renewable Energy Directive of the European Union (EU-RED);
- Renewable Fuel Standard (RFS-2) in the United States;
- California Low Carbon Fuel Standard (LCFS);
- Global Bioenergy Partnership (GBEP)
- ISO 13065-Sustainability Criteria for Bioenergy
- Roundtable on Sustainable Biomaterials in Europe;
- Bonsucro Production Standard; and
- ISCC (International Sustainability & Carbon Certification) standard.
- European Commission, 2020. Voluntary schemes

2.1.3. Agriculture

Feeding an estimated 9 to 10 billion people by 2050 without contributing unsustainable levels of GHG emissions is one of the world's key challenges. Overall food demand is projected to increase by 50%, and demand for animal-based food by 70%, over 2010 levels, according to WRI. Today, agriculture already uses half of the world's vegetated surface, a percentage that will surely increase without growth of the sector, slowly due to the effects of climate change on arable land.

Agriculture's contribution to GHG emissions, and mitigating that contribution, requires multiple measures to:

- reduce growth in demand for food and agricultural products;
- increase food production without expanding agricultural land;
- exploit reduced demand on agricultural land to protect and restore forests, savannas and peatlands;
- increase fish supply through improved wild fisheries management and aquaculture; and
- reduce GHG emissions from agricultural production.

The principal drivers of the agriculture and ranching sector's emissions are food production, processing and land use practices, which outweigh emissions from energy consumption. Thus, mitigating emissions from this sector not only involves reducing emissions from its energy consumption, but more importantly from reforming farming and ranching practices. These practices, which the World Bank estimates currently consume 70% of global fresh water, also face pressure from drought and flooding caused by global warming. The World Bank further estimates that a 15% increase in water withdrawals will be needed by 2050 to feed an additional 2 billion people (https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture).

The Parties to the Paris accord (COP 25) "recogniz(e) the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse impacts of climate change" (UNFCCC, 2015).

Agriculture's contribution to GHG emissions derive from (in order of magnitude according to the WRI): ruminant enteric fermentation, energy, rice methane, soil fertilization, manure management and ruminant wastes on pastures. Another principal contributor of agriculture—removal of forests, peatlands and savannas for agricultural expansion—results in loss of the carbon sequestration capacity of these lands.

The agricultural sector's contribution to GHG emissions is further complicated by the concentration of methane (CH4) and nitrous oxide (N2O) emissions, distinct from CO2, which calls for a different accounting of these emissions relative to the Carbon Budget. Coming out of COP 26, the EU and the United States pledged to slash methane emissions, a much more powerful contributor per unit to global warming than CO2. If achieved, the methane pledge could reduce global warming by 0.2°C, according to the announcement.

The Agriculture sector was estimated by WRI to contribute 17.2% of global GHG emissions in 2016 (inclusive of 2.2% contributed through deforestation, or change in land use, occasioned by agricultural uses.) The IPCC, along with scholarly research (Mbow et al) estimate that the food system as a whole is responsible for approximately 21-37% of annual emissions.

WRI calls for creating a "sustainable food future"—meeting food demand; avoiding deforestation; and restoring damaged or unproductive lands—to reduce poverty, promote economic development and help stop global warming, by closing three "gaps":

- A "food gap" requiring a 50 % increase in food production by 2050 over 2010 levels;
- A "land gap" requiring an estimated additional 600 million hectares (Mha) for crop and pasture lands; and
- A "GHG mitigation gap" estimated at 11 GtCO2e per year. (This is estimated as the difference between annual emissions from Agriculture and land-use change in 2050 and a target holding Agriculture's emissions to 4 GtCO2e to hold warming to 2°C.

WRI (cited above) lays out a menu of measures which taken together may meet this challenge, consistent with the UN's SDGs, by pursuing seven themes:

- Raise productivity;
- Manage demand;
- Link agricultural intensification with natural ecosystems protection;
- Moderate ruminate meat consumption;
- Target reforestation and peatland restoration;
- Require production-related climate mitigation; and
- Spur technological innovation.

Scope 1 and 2 emissions (e.g., fuel, transport, agricultural machinery) and Scope 3 emissions (e.g., embedded in fertilizer manufacture and transport) are difficult to quantify, and are included by the IPCC and others in Energy, Manufacturing and Transport sector mitigation measures.

A principal contributor of Agriculture (and the food system globally) to GHG emissions is land use change resulting in deforestation and other land clearing to create new crop and pasture lands. While WRI estimated deforestation to contribute 2.2% of global 2016 emissions, Le Quere et al (2018) estimated net land-use relation CO_2 emissions at 14% of annual emissions, with 10% directly attributable to agriculture (Mbow et al).

The Agriculture sector is responsible for about 25% to 32% of anthropogenic methane (CH_4) emissions (IEA, 2020, UNEP, 2021), and about 75% of nitrous oxide (N_2O) emissions (IPCC). Both gases have important greenhouse gas (i.e., climate-warming) properties distinct from CO_2. CO_2 has a lifespan measured in millennia when emitted into the atmosphere. By contrast, methane lasts approximately 12 years (or a lifespan measured in decades), and N_2O has a lifespan of about 114 years (or one measured in centuries). Importantly, both gases are significantly more potent than CO_2 in their global warming properties. As measured by global warming potential (GWP) models of the IPCC and others, methane is anywhere from 28-32 times, or as much as 80 times, more potent than CO_2. N_2O is as much as 300 times more potent than CO_2.

Sources of methane and N_2O emissions in the Agriculture sector primarily come from ruminant livestock (cattle, sheep, goats) for meat and dairy, and secondarily from rice cultivation.

Lynch et al (2021) note an important distinction to be made between the nature and extent of GHG emissions from the Agriculture sector as distinct from GHG (or CO_2) emissions globally. With such a short atmospheric lifespan, methane emissions may reach “equilibrium” in comparatively short order. New emissions, over the course of decades, become naturally inactive in the atmosphere. N_2O, while its lifespan is measured in centuries, also will become inactive over much shorter time span than CO_2, which is “baked into” our atmosphere for millennia once released. With this in mind, Lynch expresses concern about use of the metric “CO_2e” (CO_2 equivalent) to measure the Carbon Budget and overall emissions. He calls for a more refined calibration of the relative lifespans and potency of each of the three principal greenhouse gases (CO_2, methane and N_2O) to assess alternative pathways to Net Zero 2050:

> The appropriate balance of...stopping and/or reversing warming from methane or CO_2…is not a question that physical science can resolve. For example, how much should consumption of ruminant products be reduced in order to lower methane emissions…? There are many emission pathways resulting in the same

> …climate outcomes. Very rapid energy decarbonization could negate the need to significantly reduce ruminant methane emissions below current levels. Alternatively, dramatically cutting ruminant methane emissions could reverse significant amount of present-day warming. The optimal strategy depends on when and at what scale alternative energy generating technologies are available, the economic value of these ruminant emissions compared to CO2 generating activities, and simply how socially and politically acceptable (they will be). (Lynch, op cit)

Net Zero 2050 Mitigation measures of the Agriculture sector may be explored by Lincoln in subsequent work.

2.1.4 Urban Development

Cities cover 3% of Earth's land surface but create more than 70% of all carbon emissions, mainly from buildings, energy and transport. Currently, 54% of all people live in cities worldwide, which is projected to rise to 68% of the world population by 2050. In addition to mitigation in the form of decarbonizing urban energy generation systems and transport, retrofitting for existing buildings and for energy efficiency and requiring net zero carbon standards for new buildings, the development patterns for the expansion of existing cities and development of new cities will present additional mitigation challenges and opportunities. Urban form and development mitigation measures for the growth of cities overlap into the adaptation agenda. New cities must be designed for more resilience against the damaging effects of climate change, and in their use of power, water and food. In addition to planning for population growth, cities must plan how to adapt to global warming. There are many competing uses for the same land, including agriculture, CO2 mitigation, urban/rural adaptation strategies. While obvious priorities may place food production over mitigation, it is beyond the scope of this paper to address land resource allocation between urban areas, and land required for food production, water and natural conservation.

Urban form refers to the physical characteristics of the built living environment, including the shape, size, density and configuration of settlements and its systems network. Urban form is often the lowest-cost strategy to reduce mobility emissions, especially as reliance on internal combustion engines continues into 2050, if not beyond. How cities grow to accommodate a projected increase in the world's urban population of 2 to 2.5 billion people by 2050 will have important GHG emissions consequences. If fast-growing cities fail to adopt the right patterns of development now, emissions will be locked in for decades. Drawing on urbanist principles such as better land-use, urban design, transport planning, housing policies and practices will make net zero easier to realize.

A net zero standard for new buildings is critical to reaching overall net zero. The carbon footprint of a building must consider the Scope 1, 2 and 3 emissions described above in Section 1. Designing the building to use carbon-free electricity for space heating, water heating, and cooking will address Scope 1 and Scope 2 emissions. Scope 3 emissions are determined by the materials used for constructing the buildings. For example, research comparing CO2e manufacturing emissions for wood and conventional (concrete and steel) building materials indicates substituting wood for conventional materials reduces emissions by 69%. The comparisons found wood was beneficial across the building life cycle analysis (LCA) phases: construction, operations (emissions during the operating life of the building, typically 50 years) and end-of-life (emissions from demolition and material disposition). The relative lifespan of a mass timber building and the length of the forest rotation (number of years between planting and harvesting) influence the potential of this Scope 3 reduction. Using wood in half of new urban construction may achieve 9 percent of 2030 emissions goals. Policy (e.g., building standards) and private capital can help realize climate benefits of wood buildings.

Urban form and building densities have a direct impact on GHG emissions. There is an extensive literature on the environmental benefits of dense centralized cities in terms of lower energy consumption for mobility and housing. The Brookings Institute funded a project measuring the carbon footprint of mobility and housing in the 100 largest urban areas in the United States. It concluded that concentration of population leads to a smaller per capita carbon footprint. Despite housing two-thirds of the nation's population and three-quarters of its economic activity, the 100 largest metropolitan areas in the U.S. emitted just 56% of carbon emissions from highway transportation and residential buildings in 2005. Therefore, the average metro resident in 2005 had a smaller carbon footprint (2.24 metric tons) than the average American (2.60 metric tons). Further, large metro areas have development patterns that show promise for reducing carbon emissions.

Research suggests that urban dwellers have smaller carbon footprints than suburban or rural residents. They live in smaller, more energy efficient homes and rely less on private cars for transportation compared to people in rural areas. A Swiss study suggests that a person's carbon footprint may have more to do with the person's wealth than the location of where the live.

Compact cities have been one of the leading global paradigms of sustainable urbanism since the early 1990s. Compactness, density, diversity, mixed land use, sustainable transportation and green space are the core design strategies of compact city planning and development. Infrastructure such as roads, transit, water, sewer, electricity can be shared and the per capita costs reduced, which is of particular benefit to lower income persons.

Peter Calthorpe posits seven universal principles for solving urban sprawl and building smarter, more sustainable cities (2017). The seven principles he shared:

1. **Preserve**: natural ecologies, agrarian landscapes and cultural heritage sites.
2. **Mix:** create mixed-use and mixed-income neighborhoods.
3. **Walk:** design walkable streets and human scale neighborhoods.
4. **Bike:** prioritize bicycle networks and auto-free streets.
5. **Connect**: create a network of streets that allow many routes using varied means of transportation to the same place.
6. **Ride**: develop high quality transit and affordable bus rapid transit (BRT).
7. **Focus:** match density and mix to transit capacity; use varied modes of transportation (bicycle, public transportation, autonomous vehicle); prioritize green (carbon-free) transportation.

Research shows dense centralized cities have lower per capita emissions in comparison with low-density dispersed cities. Cars are used less, commuting distances are shorter, and buildings require less energy for heating. Muniz and Dominguez's (2020) study of larger US urban areas confirmed that urban form and spatial structure affect the per capita carbon footprint of mobility and housing, but found the effect is modest compared to other control variables, particularly total population, per capita income and temperature. Their research relies on data for gasoline and natural gas (i.e., carbon) in relation to population density. There was no discussion of the effect of decarbonizing urban energy generation, transport, or building heating, cooling and cooking.

Over centuries, human settlements evolved from being self-sufficient in food production to depending upon outlying areas for resources. The area of modern cities is too small to support their residents' demand for food and resources. Cities draw food, fiber and fuels from outlying areas. The area needed to supply these resources is known as an urban footprint. The urban footprint increases as population growth and/or consumption per capita increase.

The global carbon cycle refers to the exchanges of carbon within and among four major reservoirs: the atmosphere, the oceans, land, and fossil fuels. Carbon may be transferred from one reservoir to another in seconds (e.g., the fixation of atmospheric CO_2 into sugar through photosynthesis) or over millennia (e.g., the accumulation of fossil carbon (coal, oil, gas) through deposition and diagenesis of organic matter). The rate and extent of the warming depend, in part, on the global carbon cycle. If the rate at which the oceans remove CO_2 from the atmosphere were faster, concentrations of CO_2 would have increased less over the last century. If the processes removing carbon from the atmosphere and storing it on land were to diminish, concentrations of CO_2 would increase more rapidly than projected on the basis of recent history. The processes responsible for adding carbon to, and withdrawing it from, the atmosphere are not well enough understood to predict future levels of CO_2 with great accuracy.

Some of the materials brought into cities from outlying areas stay and accumulate. The rest are returned as gaseous, liquid and solid residuals into the air, water and soil affecting not only cities and their outlying areas, but also remote areas. Urban dwellers produce large amounts of solid and liquid waste. Solid waste can be recycled, incinerated, composted or deposited in landfills. Liquid waste such as sludge either enters natural aquifers or wastewater treatment plants. During decomposition of waste at landfills, gases such as CO2 (30%-60%), CH4 (40%-70%) and negligible amounts of volatile organic compounds are emitted.

The size of the urban footprint needs to be considered when determining a city's net carbon impact. In our current primarily linear economy, we take materials from the Earth, make products from them, and eventually throw them away as waste. In a circular economy, by contrast, we stop waste from being produced in the first place. A circular economy is a based on three principles, driven by design:

1) eliminate waste and pollution;
2) circulate products and materials (at their highest value); and
3) regenerate nature.

It is underpinned by a transition to renewable energy and materials. A circular economy decouples economic activity from the consumption of finite resources.

Drawing on principles for better land-use, urban design, transport planning, housing policies and practices will make net zero easier to realize. These principles for an integrated city include:

- Address housing needs through urban infill rather than suburban sprawl;
- When new urban areas are required, plan compact, mixed-use development, allowing people to live closer to jobs, essential services, and recreation;
- Redesign streets and infrastructure investments that prioritize mobility alternatives;
- Clean electrification of buses and waste collection fleets; and
- Design integrated policies that reduce waste and promote circularity, aligning efforts by different stakeholders through public/private collaboration.

The "15-minute neighborhood" model aims to build vibrant, mixed-use neighborhoods where all residents can reach their daily needs within a 15-minute walk of their home. The concept has become a shorthand for more walkable neighborhoods. A wider concept envisions a regional network of these neighborhoods that reflects and supports the region's racial and socioeconomic diversity as a priority.

The electrification of personal and public transport vehicles may make the densification of cities less important from an GHG emissions point of view. However, urban form has other broader impacts, particularly from an equity perspective. In developed and developing countries, creating walkable 15-minute cities provides all citizens the opportunity of walking to work. Lower income households and individuals are more likely to be reliant on pedestrian, bicycle and public transportation, and to benefit from having a full range of goods and essential services met within a 15-minute walkable neighborhood. The scale of the housing challenge becomes almost unimaginable when considering the approximately one billion people living in informal settlements, on top of the housing needed to accommodate projected population growth.

The effects of climate change are worse among poor and low income communities, in part because many live on the margins of society, in unstable structures, and in areas more susceptible to heat waves, flooding, landslides and Earthquakes. These factors are exacerbated by inadequate resources and reduced access to emergency response systems, especially in developing countries. Pollution, mostly associated as a by-product of urban landscapes, is also linked with climate change. Both climate change and air pollution are exacerbated by the burning of fossil fuels, which increase CO2 emissions, the cause of global warming.

The poor are also more likely to be subject to air pollution. In October 2018, the World Health Organization (WHO) said in a report that 93 per cent of the world's children breath toxic air every day. According to the report, 1.8 billion children breathe air that is so polluted it puts their health and development at serious risk. WHO estimates that in 2016, 600,000 children died from acute lower respiratory infections caused by polluted air. The report highlights that "More than 40 percent of the world's population – which includes 1 billion children under 15 - is exposed to high levels of household air pollution from mainly cooking with polluting technologies and fuels." In developing countries, women frequently rely on coal and biomass fuels for cooking and heating, putting them and their and their children at higher risk to the effects of home pollutants.

Creating dense, walkable cities will further social equity by ensuring more residents have access to essential goods and services. Public policies that can assist in developing dense connected cities include:

- Adopting citywide form based codes that give developers flexibility;

- Establishing policies for 15-minute neighborhoods that provide access to jobs, food healthcare, recreation without use of a personal vehicle;
- Compact growth and infill housing incentives;
- Time and demand-based charges on auto use and parking;
- Investments that prioritize mobility alternatives; and
- Introducing bans on fossil fuel transport.

Not all of the effects of denser urban development are clearly positive from a climate adaptation perspective. Urban development modifies precipitation through the heat-island effect, defined as the difference in temperature between a city and the surrounding rural area. As a city grows, it gets warmer, which adds energy to the air, causing it to rise faster, condense, form precipitation and dump it over the city or downwind of the city. This may result in extreme precipitation and flooding in some urban areas, and lower precipitation in others. This is another area where urban form that best meets mitigation goals may be at odds with adaptation measures for urban densification.

Land value capture is one mechanism to harness the value of land as it is developed to finance infrastructure and systems to help the local population. However, there are multiple competing demands on the value of land to support social equity goals and fund the type of mitigation and adaptation needed. Available research on the relationship between urban density and CO_2 generation does not provide guidance useful for estimating the land required for future urban growth based on urban development principles reflecting the decarbonization of transportation. We found little or no data or research on:

- The disaggregation of urban CO_2 emissions by sector (energy generation, heating, transportation, etc.) from current fuel sources;
- Projected CO_2 emissions under an efficient, clean electricity future (preferably at an optimum/desirable urban form and density).
- The optimal/desirable urban form and density for new development of new cities. If transportation is decarbonized, is it still helpful to have dense cities? Are there other co-benefits of density, (e.g. infrastructure efficiency, social equity) that continue to make dense cities worthwhile?
- How we can estimate the amount of land required for future urban development, and the urban footprint, and how we can change the amount of land required through climate policy?
- How we prioritize the climate change mitigation agenda in the competitive allocation of the world's usable land on a regional/global basis?

2.2. Removing GHG from the Atmosphere: Land and Nature-Based Solutions

The degree to which the energy transition contributes to achieving Net Zero 2050 by reducing GHG emissions will inform, if not direct, the degree to which land-based solutions must **remove** carbon from the atmosphere to achieve this goal. Even if the IEA's energy transition roadmap for Net Zero 2050 is fully realized on time, most estimates project land-based emissions will continue to eat away rapidly at The Carbon Budget. The IPCC projects the world's Carbon Budget will be exhausted as early as 2030, and few observers conclude, based on existing pledges from Glasgow (NDCs and NAPs filed with the UN), that Net Zero 2050 will be achieved on time. Emissions reduction measures have lost none of the urgency of their role in slowing global warming. Quite the contrary, the most recent IPCC assessment (February, 2022), details an alarming acceleration of warming and the most devastating consequences for people, cities and habitat.

Thus, it remains critical that Carbon Dioxide Removal (CDR) measures be pursued as aggressively as possible, simultaneous with emissions reduction measures. In fact, the IPCC calls for removal of immense quantities of CO2 currently in the atmosphere: 730 GtCO2e by 2100 to achieve the 1.5°C target. This amount of carbon removal equates to almost 15 times current global annual emissions. (Rogelj et al, IPCC, 2018). The IPCC defines CDR as "anthropogenic activities removing CO2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products." Such reservoirs are often referred to as (carbon) sinks.

The IPCC Special Report on Climate Change and Land (2020, revised) represents a key guide to policy makers regarding the role of land and land use policy in managing, reducing and removing GHG gases from Agriculture, Forestry and Other Land Use (AFOLU). (The IPCC Special Report omits a discussion of urban development and urban form, particularly in response to projected growth of the world's urban population through 2050 of approximately 2 billion people, and its contribution to global warming, emissions and mitigation.)

For the period 2007-2016, IPCC reports that AFOLU practices produced 13% of CO2, 44% of methane, and 81% of nitrous oxide human-caused emissions. This is estimated as the equivalent of 12.0 ± 2.9 GtCO2e per year. If emissions related to food production, consumption and waste is included, the figure increases.

The speed and scale with which land policy and land use must change to maximize their CDR potential to mitigate global warming call for urgent realignment of how governments at every level, along with the private sector, use land. A number of land use solutions that mitigate emissions conflict with many of the UN's Sustainable Development Goals (SDGs), particularly around food security, water management and biodiversity.

Roe et al in the journal Nature (October 2019), "Contribution of the Land Sector to a 1.5°C World," reviewed modelled pathways and literature of the land sector and its potential contribution to Net Zero 2050. They developed a roadmap for a number of priority land-based measures and geographic regions through 2050 to maximize their mitigation outcomes for a 1.5° C world. This roadmap seeks to ensure co-benefits with the goals of biodiversity, water, air, soil, resilience, food security and livelihoods. Further, the roadmap seeks to advance other key international goals, such as the UN's SDGs, the UN Convention on Biological Diversity, the New York Declaration on Forests (NYDF) and others. Finally, it seeks to minimize adverse impacts of some land-based solutions.

The authors conclude:

> "Transforming the land sector and deploying measures in agriculture, forestry, wetlands and bioenergy could feasibly and sustainably contribute about 30%, or 15 billion tons of carbon dioxide equivalent ($GtCO_2e$) per year, of the global mitigation needed in 2050 to deliver on the 1.5 °C target."

The climate change mitigation agenda for land policy and land use must be developed as a portfolio of solutions, with care to maximize mitigation outcomes, complement the SDGs and other key international agreements, while simultaneously minimizing adverse impacts. This will require an assessment of both (1) nature-based solutions (NBS), e.g., prevention of forest deforestation, reforestation and soil carbon land management practices; and (2) technology solutions, e.g., BECCS, biochar, DAC.

CDR measures include Nature-Based Solutions (NBS) and technological solutions. The former include practices associated with:

- Forestry;
- Wetlands and Peatlands;
- Agricultural Soil; and
- Ocean-based.

Technological CDR measures include:

- Bioenergy with Carbon Capture and Sequestration (BECCS);
- Biochar;
- Direct Air Carbon Capture and Storage (DACCS, or DAC);

- Enhanced weathering; and
- Ocean fertilization.

Land-based mitigation measures at the scale required to achieve NZ 2050, whether NBS or technological, all produce critical challenges for food and water security and biodiversity. We will review these trade-offs in the particular cases of forestry (especially afforestation) and BECCS. These trade-offs are similar to those discussed in the biofuels section above.

With issues of permanence, environmental disturbance, competition with food, water and biodiversity goals, CDR measures will likely benefit from formalized certification schemes that assure policy makers, stakeholders, emitters and investors alike of the benefits, costs, permanence and reliability of each CDR measure. The European Union has announced it will develop the necessary rules to monitor, report and verify the authenticity of carbon removals by the end of 2022.

The U.S. Department of Agriculture announced in May of 2021 its intention to develop an assessment tool for its Conservation Reserve Program. In December of 2021, the US Environmental Protection Agency issued rules to report greenhouse gases (GHGs) from facilities that inject carbon dioxide underground for long-term geologic sequestration. Numerous carbon credit markets, both governed and voluntary, contain some form of certification regime to assure sellers and buyers of carbon credits of their mitigation value. No common CDR certification standard has yet emerged, but will likely be required to establish the permanence and measured value of individual CDR projects and programs.

As noted in the preface, among Nature-Based Solutions this paper will review forestry measures and soil carbon sequestration. Among technological CDR measures, this paper will review the sink potential and land-use conflicts associated with BECCS. Discussion of other CDR measures, both NBS and technological, is deferred for possible later consideration by the Lincoln Institute.

2.2.1. Forestry

Forestry sequestration measures start with managing land use change. It will prove essential to meeting Net Zero 2050 that deforestation, degradation of forest, peatlands and coastal wetlands be minimized if not halted altogether. Since 1970, more than 270,000 square miles of tropical rainforest has been destroyed in Brazil alone, an area the size of Texas. Between 2014 and 2018, more than 26 Mha of forests were lost annually, representing a 43 percent increase for the period 2001-2013.

Yet anthropogenic deforestation is not the only risk to forest lands. Global warming itself is destroying forests at a rapid clip through drought, wildfire and pests. More than 6 million acres of California's total 33 million acres of forest burned in just the last two years. More than 100 million trees were lost in the 2021 963,000 acre Dixie fire alone. Increased tree mortality from disease and pests peaked at the end of the last five year drought in California, killing an estimated 62 million trees in 2016. The US Forest Service estimates tree die off in California from insects, disease and dehydration (excluding wildfire losses) since 2010 exceeds 172 million trees.

Deforestation must decline by 70 percent by 2030 and by 95 percent by 2050 to meet the 1.5°C target. A Norwegian energy executive notes that "(i)f deforestation were a country, it would be the third largest emitter in the world." (Rebora, Equinor, 2022).

The IPCC Special Report on Land (op cit, 2019) found that the CDR potential for afforestation and reforestation ranges from 0.5 to 10.1 GtCO2e per year. The high end of this range equals China's total GHG emissions in 2010. Notably, however, this upper end of the range assumes reforesting all grazing lands, illustrating the direct threat that reforestation at scale represents for food and water security, and for biodiversity. At the same time, the IPCC Report states: "reducing deforestation and forest degradation rates represents one of the most effective and robust options for climate change mitigation, with large mitigation benefits globally." It notes that the benefits of improved forest management is one of only nine actions the IPCC identifies with positive outcome across all five challenges: mitigation, adaptation, desertification, land degradation and food security. Forests themselves are part of the Earth's overall climate. The IPCC report calls for reducing tropical deforestation immediately:

- support countries rich in forestlands with adequate and well-designed incentives and management practices;
- reduce competition for land (among forests, crop and range lands) through "no regrets" measures to increase food productivity, reduce food loss and waste;
- support the role of indigenous people as stewards of forestland, strengthen their land tenure rights, and provide economic support; and
- reduce GHG emissions, which negatively affect the health of forests.

Rogelj et al (2016) modeled the CDR potential of forestation land use changes at between 0.6-8.2 GtCO2e per year. In 2019, Roe et al estimated the mitigation potential for reduced deforestation at between 0-5.8 GtCO2e per year. A cost analysis by Austin et al (2020) projects mitigation potential of forestry measures across four activities and sixteen regions based on carbon prices ranging from $5-$100/ton CO2. Austin and her colleagues projected 0.6-6.0 GtCO2/year in global mitigation by 2055. Their cost estimate, with a very wide range of US$2 billion to US$393 billion per year, reflects the high degree of uncertainty in forecasting mitigation, cost, and land area required for such land based measures.

The Austin estimates project a need for an additional 415-875 million hectares (Mha) in forestlands to achieve these mitigation estimates, using carbon prices of US$35-100/ton CO2. Roe models a similarly massive increase in forested lands to achieve the 1.5°C target from CDR forestation measures. Under her alternative pathways, she reports "the full range for natural forest change is large, from about 300 Mha decrease to about 1,000 Mha increase in 2050 compared with 2020, primarily due to the inclusion or exclusion of afforestation and reforestation…"

Austin estimates that for forests to contribute about 10 percent of the mitigation needed to limit warming to 1.5°C, carbon prices will need to reach USD$281/tCO2 by 2055. By comparison, in March 2022, compliance market carbon credits sell for approximately €67 in Europe, USD$30 in California, and between USD$5-10 in selected voluntary markets. Clearly, different models, pathways and economic assumptions yield different estimates of mitigation potential.

In addition to their CDR potential, maintaining forest lands provides many co-benefits consistent with the UN's SDGs. These include supporting soil health, water filtration and conservation, maintaining biodiversity, providing security for indigenous lands and their residents, and offering potential employment through forestry management. The capacity to deploy forestation measures at scale exists today.

Forestation, in the form of reforesting formerly logged or displaced forestlands, and afforestation has very large potential for carbon sequestration, both from photosynthesis and from transfer to the soil by litter fall, deadwood and roots. But there are offsetting concerns about forestation as a CDR measure. One such concern is the effect of expanding forestlands on albedo, the ability of the Earth's surface to either absorb or reflect solar radiation. Forestation lowers the albedo, potentially resulting in surface temperature increases. Albedo effects vary by latitude, with arboreal forests subject to cooling and tropical forests subject to warming trends. Older growth forests are subject to carbon saturation, limiting their additional capacity to serve as sinks. And forests are vulnerable to environmental degradation largely beyond human control: drought, wildfire, pests. As we have noted, in the last two years alone, more than 6 million acres of forestland burned in California. Thus, the CDR potential of forestation is uncertain relative to scale and permanence of the carbon sink.

The wide variation in the projections of mitigation potential (GtCO2e/year), cost ($/ton CO2) and land area requirements (Mha) of forestry CDR measures poses an acute challenge for policy makers, stakeholders, project sponsors, investors and analysts in managing the transition to Net Zero 2050. We saw similar uncertainty in the Biofuels discussion above. Moreover, the potential for forestry co-benefits to conflict with adverse outcomes (competition for land, water, habitat, and adverse impact on climate and environment) call for a reliable, interdisciplinary framework of all mitigation measures across the Net Zero 2050 transition. Such a framework must account for emissions/sequestration, cost and land consumption. It must further afford a means to weigh co-benefits against negative outcomes.

2.2.2. Soil Carbon Restoration

Soil represents an enormous carbon sink globally, holding three times the amount of carbon in the atmosphere. Through land use change and agricultural practices, soil has lost by one accounting more than 800 GtCO2e, with many cultivated lands losing 50 to 70 percent of their carbon content. (American University, 2020; Fuss et al 2018; Zelikova et al 2020; P. Smith et al, 2016).

A promising land-based CDR measure may accordingly be pursued in practices aimed at restoring the carbon content of soils, especially on agricultural lands. Soil carbon enrichment can play a potentially material role removing CO2 from the atmosphere. Practices which enhance the soil carbon sequestration include using plants with deeper root structures, agroforestry, sowing cover crops, adding carbon-rich materials to soil such as biochar, leaving crop residue to decay, applying compost or manure, reduced tilling, and crop rotation.

Soil carbon enrichment strategies bring important co-benefits to land stewardship. In the form of soil quality and crop productivity, capacity for water and nutrient retention, resilience against flood and drought, reduced need for fertilizers. These strategies have the added benefit that they can be carried now, without pursuit of costly or unproven technological advances. Current technology and practices must be scaled up by a very large to achieve these benefits. Yet methods to measure, monitor and verify specified quantities of sequestered carbon are challenging and costly.

However, there persists great uncertainty regarding the permanence of soil carbon sequestration practices. They must be carried out indefinitely, without interruption. Reverting to past practice will result in release of carbon back into the atmosphere. Further, carbon saturation of soils may be reached in a matter of decades, limiting the sequestration value of these measures. The IPCC notes that global warming may further compromise the capacity of soils to absorb carbon. Thus, the significant limitations to these practices is reversibility and saturation. Moreover, to reach the gigaton scale of carbon removal, agricultural practices will have to change across millions of small farmers and land owners worldwide.

This uncertainty results in a wide range of estimates regarding the potential for soil carbon enhancement to sequester carbon. The IPCC estimated in its report that carbon sequestration in croplands and grasslands may contribute between 0.4-8.6 GtCO2 per year. The top end of this range represents 26 percent of global GHG emissions in 2021 (IEA). The European Parliamentary Research Service (EPRS, 2021) estimates the potential value at 2-5 GtCO2e per year, at a cost per ton of CO2 ranging from $0-100.

American University's Institute for Carbon Removal Law and Policy reports the cumulative potential of soil carbon removal practices at between 104–130 $GtCO_2$ by the end of the century. Roe and her colleagues (op cit) estimated in their pathway for the contribution of land to a 1.5°C world that by 2050 soil carbon enhancement measures may sequester 1.3 GtCO2e per year, or 9 percent of their model's projection for the entire land sector's contribution to emissions reductions and carbon removal. Roe's pathway identifies as priority regions for these measures: China, EU, US, Australia, Brazil, Argentine, India, Indonesia, Mexico, and Sub-Saharan Africa.

To reach this level of carbon removal, soil sequestration practices will require widespread technical assistance, financial incentives, research into best practices and development of a reliable reporting, monitoring, verification and enforcement regime.

2.2.3. Wetland and Peatland Preservation and Restoration

Wetland and peatland preservation and restoration CDR measures are beyond the scope of this paper, but merit a brief mention. The EPRS and IPCC report that annual CDR potential of restoring coastal wetlands ranges from 0.2-0.84 GtCO2e, while restoring degraded peatlands may contribute from 0.15 to 0.81 GtCO2e. But there are tradeoffs here as well. Most wetlands are considered carbon sinks in the long run, and do so with much higher carbon concentration on small areas of land compared to other NBS CDR measures such as forestation and soil carbon restoration. At the same time, wetlands serve as a source of methane emissions, and restoration may take a century or more to serve as a net carbon sink. Some researchers note that mangrove wetlands emit limited amounts of methane while absorbing considerable amounts of carbon. The EPRS cites mangrove wetland restoration costs at US$510 per ton of CO2. These higher costs may be offset by some of the co-benefits of wetland restoration, such as flood protection and mitigation, habitat and biodiversity preservation and improvements to water quality. Other observers note, however, that with global warming and its attendant sea level rise, coastal wetland restoration (and preservation) may be relatively short-lived.

But preserving peatlands may be even more vital if a massive release of carbon is to be avoided. In the Republic of Congo and the Democratic Republic of Congo lies the largest peatland in the world, some 55,000 square miles, or the size of Britain. Researchers at the United Nations Environmental Programme (UNEP), along with Dargie et al, estimate these peatlands contain approximately 30 GtCO2e, an amount roughly equivalent to total global annual emissions in recent years.

A reported, and to some questionable, announcement of the discovery of oil beneath these peatlands underscores the importance of land policy practices aimed at preserving critical natural carbon sinks. The pledge of $1.5 billion to help preserve the Congo peatlands noted earlier in this paper represents a start toward paying poorer countries the market value needed to preserve such peatlands. This becomes imperative in the face of competing development and economic pressures such as oil exploration, logging, clearing for cropland and pastures. Beyond the need to finance the market value of Congo (and other tropical) peatland preservation, it will prove critical to secure enforceable land rights for native and indigenous people who may be the most effective stewards of this irreplaceable land carbon resource.

As important as tropical peatlands such as the Congo basin are, they pale in comparison to the retained carbon of permafrost lands in the northern hemisphere. Wilkerson et al (2021) note that permafrost covers one quarter of the Northern Hemisphere's land area, and, shockingly, contains 1.5 trillion metric tons of organic carbon, twice as much as contained in the Earth's atmosphere today. The IPCC's Sixth Assessment reflects the lack of scientific consensus of how much, and how fast the thawing of permafrost will release CO2 in the atmosphere:

> "The IPCC's latest report instead makes a best estimate of the range of carbon that permafrost could potentially expel. It then accounts for that range when estimating the world's remaining carbon budget—the amount of CO_2 that the can still be emitted—for meeting Paris Agreement targets, says Charlie Koven, a carbon cycle scientist at Lawrence Berkeley National Laboratory and one of the lead authors of the report. While not ideal, this approach is 'a reflection of the urgency of the climate crisis,' he says. 'We don't have time for a perfect solution. We need to act on the knowledge that we do have.'" (Wilkerson et al, *Scientific American,* August 11, 2021).

Understanding, and solving, the peatland and permafrost carbon sink preservation challenge represents a critical land use CDR undertaking if a Net Zero 2050 (and beyond) goal is to be achieved.

2.2.4. BECCS

Bioenergy with carbon capture and storage (BECCS) technology depends on cultivating, harvesting and transporting crops (biomass) for burning to generate electricity, typically via steam generation. Simultaneously, the CO2 waste gases are captured from the burn, compressing them into liquid form, and injecting them for very long (centuries) storage into the Earth. Alternatively, BECCS biomass feed stocks may be derived from collecting, transporting and burning residues from forestry, agriculture and wood products industries. The carbon capture potential for BECCS technologies is substantial. Fuss et al (2018) could remove 0.5 -5.0 GtCO2 per year, at a cost of US$100-200 per ton. IPCC scenarios with a 66 percent or better chance of limiting global warming to 1.5°C by 2100 call for more than double this amount of sequestration: a median of 12 GtCO2 per year. Fajardi et al (2019) at the Grantham Institute of the Imperial College of London in providing a "reality check" on the deployment of BECCS, cite Rogejl (op cit, 2018) and Huppman et al (2018) referencing sequestration levels up to 22.5 GtCO2 per year by 2100.

Most integrated assessment models (IAMs) for pathways limiting warming to 1.5° to 2° C call for large scale deployment. Roe (op cit) models in one pathway BECCS comprising 7 percent of total land-based mitigation, or 1.1 GtCO2 removal per year by 2050.

But a massive deployment of BECCS will, by many observers, require between 0.4 to 1.2 billion hectares of land (25 percent to 80 percent) of current global cropland (Harper et al, 2018; Field et al, 2017), or 31-58 Mha per CtCO2 (Roe, op cit). The IPCC climate models require 109-990 million hectares of land for BECCS, with averages between 380-700 million hectares. The WRI notes that such land requirements for BECCS would consume 24 million hectares per, or seven times the global rate of expansion for soybean and sugarcane combined. Water consumption for massive scale (e.g., 12.5 GtCO2 per year) BECCS deployment is further unsustainable, even with wide variation among analysts:

- 5.3 to 24.4 billion cubic meters (Smith and Torn 2013);
- 0.72 billion cubic meters per year (Smith et al, 2016);
- 3.6 to 9.7 billion cubic meters per year (MONET model, cited by Fajardi, 2018).
- Fajardi notes total global agricultural water consumption at 8 billion cubic meters per year.

These land and water consumption requirements push up against planetary boundaries for both, and if substantiated, will severely restrict the use of BECCS as a CDR measure. Substantial disagreement, if not controversy, exists surrounding the potential for BECCS to provide very large scale solutions to provide both renewable energy (burning biomass; see the above discussion of Biofuels for co-benefits and land use conflicts) and deep, long term carbon sequestration. Serious concerns are raised by the unsustainable land and water requirements, noted above. Beyond that, BECCS technology threatens conflict with land use and SDG goals. Extensive use of land, water and fertilizer (nitrogen, phosphorus) could cause deforestation on a massive scale, in turn threatening food security and food prices. This would simultaneously increase GHG emissions, diluting the net CDR benefits of BECCS. Such large scale deployment would also threaten biodiversity, provoke biophysical changes to surface energy transfers.

The technologies to grow biofuels, and to capture and liquefy CO2 from flue gas, exist today widely in separate applications. However, the combined application of these two technologies (as of 2020) has been limited to one biofuel plant in the United States, and two combined heat and power demonstration projects in the UK and Sweden in 2019 (EPRS, op cit).

Most pathways (IAMs) to limit global warming include some component of BECCS. However, there appears to be no standard accounting for adverse environmental, food production, societal, land and water effects among these models. Widespread agreement exists that governance (regulation) of BECCS feedstocks, and sustainable land and water use and habitat protection practices will be required of BECCS to prove itself as a valuable component of the balanced land-use CDR measures the world will need to limit global warming. Solutions to render BECCS sustainable at speed and scale include properly removing crop residues from the field without causing soil depletion and erosion, growing biomass feedstock on marginal lands, or employing algae as a large scale feedstock.

Governance protocols will likely be required to limit BECCS usage to sustainable scale, both in modeling and policy (certification) frameworks. This will require setting clear standards for resource constraints and use (land, water, habitat, environmental/climate impact), as well as for carbon storage and energy efficiency performance.

Finally, cost constraints (as with many Mitigation measures), must be resolved. Reducing the financial risks of CCS strategies, Gough et al (2018) and Kemper (2015) estimate carbon pricing will need to reach $30-280 per ton CO2 to make BECCS power production financially feasible. To date, the EU Emissions trading Systems and California's Carbon Credit Market have not achieved prices at these levels. And there may be structural problems with the global value chain for BECCS. Regions with high biomass production potential (South America, Sub-Saharan Africa) likely do not possess the subterranean carbon storage capacity of North America, Europe or Japan.

Fajardi summarizes a pathway for considering the deployment of BECCS as an important measure in the land-based CDR tool kit:

- Broaden the scope of the biomass sustainability standard;
- (S)et clear standards for biomass sustainability: …on carbon intensity of biomass, feedstocks…, water, CO2, …energy efficiencies, …(and) carbon breakeven time.
- For example, the low carbon fuel standard in California…;
- …(T)he UK Bioenergy strategy includes a sustainability criterion ensuring a minimum of 60% emission reduction from the average European power carbon-intensity for bioelectricity…
- The more recent European Renewable Energy Directive II goes further: …large scale heat and power biomass plants deliver an 80% emissions reduction compared to fossil fuel, with a life cycle emissions accounting framework that includes land-use change emissions. (Fajardi, op cit)

Such certification and enforcement protocols will prove valuable in properly scaling sustainable role for BECCS in the energy transition and among land-based CDR measures.

3. LAND AND THE ADAPTATION AGENDA

The world's efforts to stem GHG emissions has proven far from adequate to protect the planet from what are now acknowledged as the "baked in" effects of global warming. The climate change Adaptation agenda is meant to address the impacts of a warming planet, from sea level rise to drought to wildfire to storms to floods, and to famine to habitat destruction.

> We must invest in a massive effort to adapt to conditions that are now inevitable: higher temperatures, rising seas, fiercer storms, more unpredictable rainfall, and more acidic oceans….Adaptation is not an alternative to a redoubled effort to stop climate change, but an essential complement to it. Failing to lead and act on adaptation will result in a huge economic and human toll, causing widespread increases in poverty and severely undermining long-term economic prospects.
>
> The Global Commission on Adaptation
> September 2019

The costs and risks of climate change are sobering. A 2018 UN report estimated that from 1998 to 2017, climate-related and geophysical disasters caused 1.3 million deaths and $2.9 trillion in economic losses globally. (House and Wallemacq, 2018). More than 90 percent of urban areas are coastal, exposing more than 800 million urban dwellers to the risk of sea-level rise and coastal flooding by 2050 (C40 Cities, 2021, 2018; C40, Global Covenant of Mayors, Acclimatise, Urban Climate Change Research Network, February 2018). In 2019 the Global Commission on Adaptation forecast that about two thirds of the world's population could suffer "water-stressed" conditions by 2025.

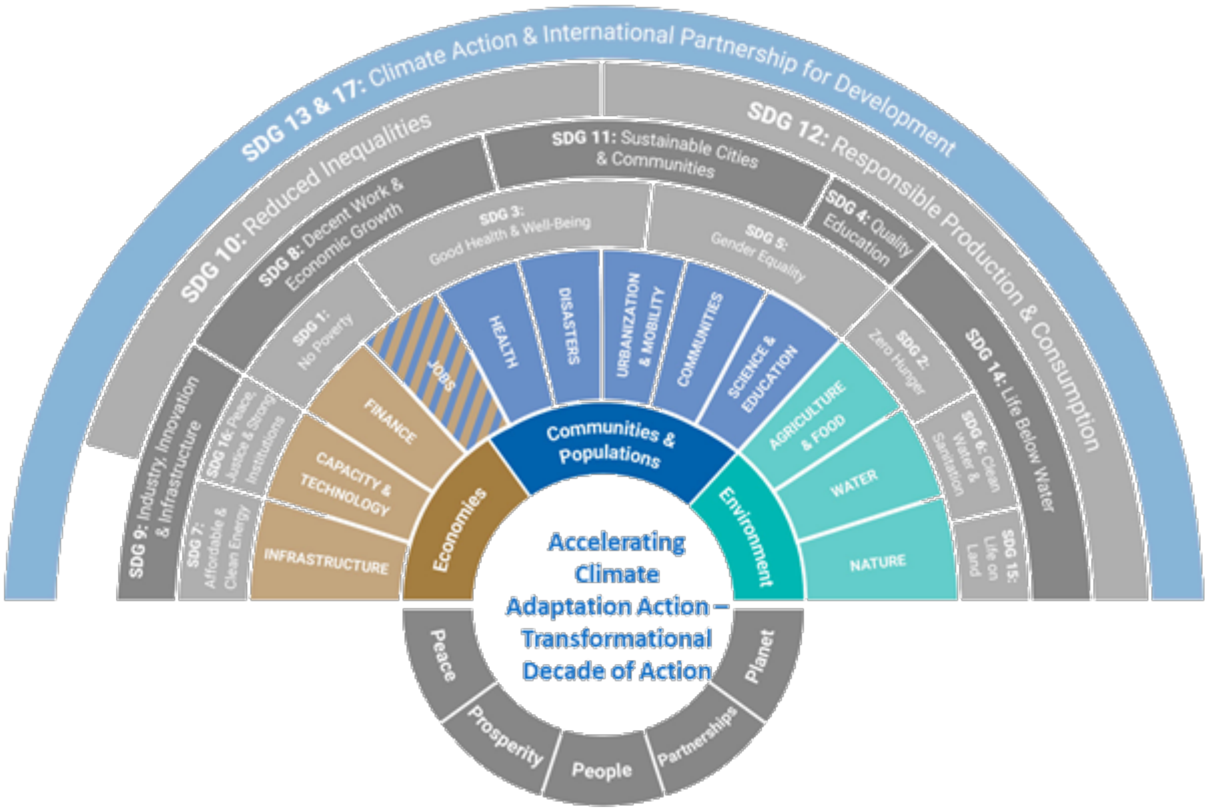
The toll for individual cities stacks up. In 2018, Cape Town nearly ran out of water. (Edmund, 2019). Patna, Gaya, Bhagalpur and other cities in eastern India lost hundreds of residents and outdoor work was banned during a 2019 heatwave. (Al Jazeera, 2019). In 2020, flooding in Jakarta killed 66 people and displaced more than 36,000. (Time, 2020). In 2018, the Camp Fire in Northern California destroyed the town of Paradise, with an official death toll of 85. News outlets reported an additional 50 deaths caused by the fire. (Los Angeles Times, San Jose Mercury News, 2020). During the unprecedented heat dome event in the Pacific Northwest in 2021, Washington State placed the official death toll at 95, but the New York Times reported a "hidden death toll" from the event at more than 600. (NYT, August 11, 2021). Winter Storm Uri hit Texas in 2021, leaving close to 4.5 million homes and businesses without power at its peak, killing more than a hundred people, causing an estimated $295 billion in damage. (Hobby School, University of Houston, 2021). Uri laid bare the inadequacy of virtually the entire power grid in Texas to withstand storms such as this.

There is no universally agreed to adaptation agenda, let alone its attendant finance needs. There is wide variation and uncertainty in the literature regarding adaptation measures and their costs. This disagreement reflects lack of consensus around climate change scenarios (the degree and pace of warming, population growth, economic growth, uptake of mitigation measures), sectors to be covered, time frames, location and costs for specific adaptation measures. A key challenge is the degree of uncertainty surrounding how fast and how much the planet will warm. Different levels of warming, of mitigation, of wet or dry weather patterns, all affect the kind and extent of adaptation measures required.

The Global Commission on Adaptation (GCA) was launched in 2018 by the leaders of 23 countries in an effort to elevate the climate change adaptation agenda.

Principal areas of focus for adaptation measures, as identified within the Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) of 26 developing countries, were agriculture (26%), infrastructure (23%), water (15%) and disaster preparedness and recovery (13%), or more than 75% of total costs. (UNEP, "The Gathering Storm," 2021).

The Climate Adaptation Summit 2021 reported out an "Adaptation Action Agenda" which is broad and general in its scope, and which seeks to integrate adaptation measures with the UN's Sustainable Development Goals (SDGs) as depicted in the chart below.



Source: https://adaptationexchange.org/adaptationActionAgenda

Since 2014, the UN Environment Programme (UNEP) has published and updated its Adaptation Gap Report (AGR), an effort to identify and measure the cost of adaptation measures across a number of countries against available finance for adaptation. Quantifying this gap is challenging. Estimates have increased continuously each year, by orders of magnitude. The most recent AGR (2021) examined the National Adaptation Plans (NAPs) (https://www.unep.org/resources/adaptation-gap-report-2021) and Nationally Determined Contributions (NDCs) of 58 developing countries, and compared the adaptation costs among developing countries with its estimates from 2016. The 2016 AGR report estimated the annual adaptation finance needs between $140 billion to $280 billion. The 2021 report, extrapolating (using per capita costs and population estimates) from the NDC and NAP reports of 58 developing countries, estimates financing needs at $250 billion per year by 2030. The Report concludes that adaptation financing needs in developing countries are five to ten times greater than finance currently provided by developed countries and development finance institutions (DFIs), and others.

The 2021 AGR notes that numerous low-cost adaptation measures with high benefit-to-cost ratios may, and should, be pursued in the short term. These so-called "no-regret and low regret options" include weather and climate services, sustainable soil, forest and land management measures, water efficiency and capacity-building.

The most recent AGR report mirrors the GCA's reported distribution of adaptation funding priorities among the 26 developing nations' NAPs:

1. Agriculture (food):	26.0%
2. Infrastructure:	22.6%
3. Water:	15.2%
4. Disaster:	12.5%
Total:	**76.3% of total adaptation finance needs**

3.1. Adaptation and Land Policy

Much of the Adaptation agenda requires engagement with land policy and land use. A few illustrative examples:

- Will cities, states and nations act to protect urban populations from sea level rise? By erecting massive sea walls, pursuing wholesale reconstruction of flood control, drainage, water and sanitation infrastructure? Or will they manage "strategic retreat" from low-lying coastal areas, requiring the relocation of tens of millions of people and countless businesses, facilities, institutions, homes and related infrastructure?
- How will cities remake their street grid, and their transportation systems, to support a transition of the transportation sector away from fossil fuels?
- How will cities, states and nations provide land resources and rights of way to accommodate the development of a resilient grid and renewable energy generation sector? Will this require extensive new rights of way for distribution of renewable energy from solar and wind resource-rich land to population centers? What role will community-level and micro-grid generation and distribution play in meeting the renewable energy demands of unserved groups and growing urban populations?
- How will cities, regions and states assure the provision of safe drinking water, and adequate sanitation?
- How will cities grow sustainably (i.e., consistent with the Mitigation requirements of a Net Zero 2050 agenda, and with the Adaptation agendas required by climate change? How can such urban population growth (projected to reach 2 billion people by 2050) be managed consistent with the UN's SDGs?
- How can the disparate impacts of climate change, felt disproportionately by very low income people within developing economies, be mitigated by equitable land

policy and land use? How can land-based solutions for mitigation and adaptation advance equitable growth, protect indigenous populations, promote health and economic prosperity?

- How must agricultural and ranching land use practices change in the face of climate change? Food production and processing? Distribution? Consumption? Waste?
- How must land management change to preserve biodiversity in the face of the demands on land for mitigation, adaptation and population growth, and climate-induced migration?
- How must management of scarce water resources change in increasingly drought-prone regions? In flood-prone regions? How will the competing demand for water for people, agriculture and biodiversity be met in the face of a changing climate?
- How will rich countries pay for the adaptation needed by low income countries, and predominantly caused by the emissions of these wealthier countries?

The GCA—the Global Center on Adaptation and the WRI are GCA's managing partners—calls for a revolution in how the world understands the impacts of climate change, plans for adaptation to those impacts, and organizes the scale of financing necessary to adequately respond.

GCA advocates that this revolution be pursued in six key areas:

1. **Food**
   a. Sharply increase agricultural research and development.
   b. Better align government policy, finance, subsidies and incentives with long-term sustainable and high productivity practices.
   c. Provide better access to information, technology and finance to support small farmers.

2. **Natural Environment**
   a. Emphasize the use of nature-based solutions (NBS) to protect watersheds, coastal zones, cool cities and complement infrastructure.
   b. Accelerate progress on biodiversity (e.g., the Convention on Biological Diversity).
   c. Properly value natural assets in land use, land policy and financial decisions.
   d. Increase public and private resources for natural protection.
   e. Recognize, and realize, the potential of NBS to provide a third of the CO2 mitigation needed to limit global warming to 1.5°C.
3. **Water**
   a. Accelerate investment in watershed protection and water infrastructure.

   b. Dramatically improve water efficiency and water allocation.
   c. Integrate climate risks of drought and flood at all levels of water planning and management.

4. **Cities**
   a. Provide solutions for coastal cities susceptible to coastal flooding: infrastructure.
   b. Improve information on climate risks in planning and delivering urban services.
   c. Strengthen local capacity.
   d. Maximize NBS in response to water and heat risks.
   e. Upgrade quality, safety and resilience of housing for hundreds of millions of people living in informal settlements.
   f. Increase climate-resilient investments, and capture value from adaptation benefits.
5. **Infrastructure**
   a. Include ports, roads, power, sanitation, sewer, communications systems.
   b. "Climate-proof" existing infrastructure; plan new infrastructure for resilience.
   c. Upgrade storm water drainage, sea level rise measures.
   d. Develop public-private financial partnerships that share the costs and benefits of resilient infrastructure.
6. **Disaster Risk Management**
   a. "Proactively yet voluntarily" move people and assets out of harm's way through improved planning and investing, based on better forecasting.
   b. Warn and prepare; prevent loss of life.
   c. Provide social safety nets.

GCA organizes its recommendations for Adaptation finance around four actions needed simultaneously:

1. Shift how investment decisions get made, based on consensus metrics for climate impacts, portfolio risk assessment and resilience ratings;
2. Increase and improve the effective use of public finance;
3. Provide adequate disaster finance, recovery and insurance resources; and
4. Maximize private sector capital investment in Adaptation and Resilience.

3.2. Adaptation Finance

Overarching the entire adaptation agenda is a critical need to massively and rapidly increase the flow of public and private capital. Adaptation financial commitments to date, to the extent they are measured, represent a fraction of the investment capital provided to the Mitigation agenda. This is due to several factors:

1. Uncertainty surrounding the projections of climate change impacts, their speed, scale, location and severity.
2. Mitigation finance, especially in energy sectors, offer market financial returns, albeit often with declining subsidies, risk mitigation and concessionary financial terms required. Adaptation measures often require outright subsidy.
3. Lack of consensus surrounding the specification of adaptation measures and their costs.
4. Lack of capacity at the local and state government levels, especially among developing countries.
5. Lack of financial resources among developing countries, which must rely on capital—both in the form of grants and concessionary finance—from wealthy nations and institutions.

The UNEP Adaptation Gap Reports (AGRs) cited above provide a rough measure of Adaptation capital requirements. The AGR reports are drawn from the NAP and NDC reports of developing countries. These reports themselves often lack specificity regarding measures, scale, time frame, and quantified costs based on verified capital expense modeling.

Several international funds provide direct investment in climate adaptation, and provide quantified reports of their activities. These include among others the Adaptation Fund, the Green Climate Fund, and the Global Environment Facility. A wide range of DFIs, sovereign aid agencies, multilateral and bilateral Adaptation investments have been made to developing countries. However, the large majority (nearly 75%) of Adaptation finance is domestic, that is, funded by and for the country in question.

3.3. Radical Uncertainty: Planning in the Face of the Unknown

The pace and scale of global warming depends on the interaction of multiple climate, economic, population, technological, land use change, emissions and carbon removal measures. The complexity and multiplicity of interactions, and their divergent outcomes, plague forecasts of global warming and its effects with "radical uncertainty." How fast, and how much, Antarctic sheet ice melt and sea levels rise? How and to what degree will global diets shift to less resource-intense crops and animal products? How fast and how thoroughly will the energy transition to Net Zero occur? Will new, yet unproven and even undiscovered, technologies to mitigate GHG emissions emerge, how fast and at what scale? Will deforestation be slowed, stopped, and reversed? How will new cities be built and existing cities grow? What effect will increasing food and water insecurity slow and depress population growth? Will changing ocean currents radically disrupt centuries-long weather patterns (e.g., the Gulf Stream)? What effect will increasing ocean acidity have on the ability of the world's fisheries to feed the planet? A rich literature has emerged over the last 20 years, exploring the constraints and effects of uncertainty in planning for climate adaptation. A review of this literature is beyond the scope of this paper, but may be sampled here.

Yet uncertainty cannot be used as an excuse for inaction. The IPCC's Sixth Assessment of Impacts, Adaptation and Vulnerability published in February 2022 squarely addresses the Adaptation dilemma:

> Given the rate and scope of climate change impacts,…actions on…implementing adaptation are insufficient. Current adaptation-related responses across all sectors and regions are dominated by minor modifications to usual practices…(to deal) with extreme weather…Long-term risks…require more extensive, transformative changes in our behavior and infrastructure. According to our new report, the world is currently under-prepared for the coming climate change impacts, particularly beyond 1.5°C global warming…
>
> Climate Resilient Development means reducing exposure and vulnerability to climate hazards, cutting back GHG emissions and conversing biodiversity are given the highest priorities in everyday decision-making…on all aspects of society including energy, industry, health, water, food, urban development, housing and transport. It is about successfully navigating the complex interactions between these different systems so that action one area does not have adverse effects elsewhere (maladaptation) and opportunities are harnessed to accelerate progress towards a safer, fairer world.
>
> IPCC, op cit

The World Bank, in its Adaptation Principles Guide acknowledges the "large uncertainty on future climate change" particularly at the local level. They conclude the need to design adaptation strategies within a framework of risk management and "continuous learning." The World Bank Guide emphasizes the need to avoid measures designed for a precise scenario, and rather prioritize those that are "robust and flexible."

Mark Smith and John Matthews, in their work on adapting water policy and management to inevitably of climate change, write eloquently on managing uncertainty:

> Climate-resilient water management…contains two key elements: defining robust actions that perform well across a wide range of possible future climates, and defining flexible actions to climate shocks and stressors and long-term uncertainties in future climat4e change impacts….
>
> If we can build resilience by managing water, we can move from a reactive, defensive approach to climate change to imagining how we can thrive….Our response to climate uncertainty and looming impacts should be neither despair not inaction but courage and hope; we should be choosing the future we want to move toward, and finding valid and realist means of reaching that future.
>
> Smith and Matthews, 2019

3.4. Adaptation Frameworks

Given the complexities and uncertainties surrounding adaptation to climate change, much of the effort to help nations, regions and cities respond has focused on providing "frameworks", guides, research, planning, funding and technical assistance. Summarized below are several such initiatives. This summary is neither intended as comprehensive or an evaluation for efficacy. Numerous important efforts are not reviewed. For example, the African Adaptation Acceleration Program, lessons learned from the discontinued Rockefeller Foundation 100 Resilient Cities (100 RC) program, and others.

Rather, we summarize important efforts which provide wide-ranging guidance on how governments, particularly in partnership with citizens and the private sector, can plan, manage, pay for and learn from best practices to date in adaptation. This field is changing and learning fast. Partly from necessity as the perils of climate change manifest in ever more costly and dire fashion, and partly as political will grows in response. Summarized below are the following Adaptation frameworks:

- IPCC Sixth Assessment of Adaptation Priorities;
- National Adaptation Plans sanctioned by the UN;
- European Union Adaptation Guidance to Local and Regional Authorities;
- Climate Adaptation Summit 2021 Priority Actions;
- Global Commission on Adaptation 2021 Guidance on Key Sectors;
- World Bank Adaptation Principles for ministries of finance and economy; and
- C40 Cities/McKinsey Sustainability Focused Adaptation Approach

3.4.1. IPCC Sixth Assessment of Adaptation Priorities

IPCC's Sixth Assessment: Climate Change 2022: Impacts, Adaptation and Vulnerability (op cit) paints a dire picture of accelerating and worsening effects from global warming beyond previous estimates. In its Assessment, the IPCC stresses the importance of Adaptation to "generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation." The assessment establishes two principal measures to assess adaptation actions. The first is feasibility, defined as the capacity for implementation. Feasibility is influenced by multiple, factors, which vary geographically and temporally, and in response to changing climate dynamics. These factors include geophysical, environmental and ecological, technological, economic, socio-cultural and institutional capacity.

The second measure is effectiveness, the extent to which an adaptation strategy will, or does, reduce risks from a changing climate.

The IPCC then categorizes Adaptation measures by sector, which among others include:

- Water: Inland flooding measures include early warning systems and levees, enhanced natural water retention by restoring wetlands and rivers, land use planning (e.g., building prohibition zones, upstream forest management. Farm-related water measures include water management and storage, soil moisture conservation and managed irrigation. (The IPCC notes that the effectiveness of water conservation and management strategies decline as global warming increases.
- Food Production: Measures include cultivar improvements, agroforestry, farm and landscape diversification and urban agriculture, environmentally sustainable management of fisheries and aquaculture.
- Forests and peatlands: Strategies include conservation, protection and restoration; improved forest management, adjusting tree speciation for improved resilience to wildfire, pests and disease.
- Urban and rural settlements and infrastructure: IPCC calls for urgent provision of basic services, infrastructure, diverse local economies, strengthened local food provision, especially in service to low income and marginalized groups. Increasingly urban adaptation measures are constrained by institutional, financial and technological access and capacity. Globally, more investment is directed toward physical infrastructure than social or natural needs, with little investment in informal settlements home to the most vulnerable.
- Sea level rise: Characterized as a "distinctive and severe adaptation challenge," and noting the extreme uncertainty of the speed and extent of sea level rise, the IPCC calls for effective responses which are combined and sequence, planned well in

advance, aligned with sociocultural values and development priorities of the locality, and supported by inclusive community engagement and planning.

3.4.2. National Adaptation Plans: The United Nations Framework

The United Nations COP 16 in Cancun in 2010 established the national adaptation plan process (Cancun Adaptation Framework—CAF). The CAF enables countries to identify medium and long term needs, strategies and programs they must pursue to adapt to the effects of global warming. Twelve years later, progress has been slow (National Adaptation Plans 2020). Nevertheless, NAPs remain a vital tool for countries to establish adaptation strategies which will guide the planning, specification, costing, financing and implementation of a country's comprehensive response to the growing and accelerating effects of climate change. A number of NGOs and DFIs provide resources to nations, especially low income and least developed countries, to help prepare sound National Adaptation Plans (NAPs). These include:

- **NAP Global Network** was established in 2014 at the 20th session of the Conference of the Parties (COP 20) in Lima, Peru, initiated by adaptation practitioners from 11 developing and developed countries. More than 1,500 participants from more than 150 countries work on national adaptation planning and action, and has delivered direct support to more than 50 countries.
- **UNFCCC Least Developed Country Expert Group (LEG)** provides technical assistance and guidance to LDCs in formulating their NAPs. They published a 2020 report on NAP Progress.
- **UNFCCC** publishes a list of NAPs submitted to date by developing countries;
- A report on NAP lessons learned and best practices; and
- A Database of resources for Adaptation and Resilience.
- **National Adaptation Plan Global Support Programme (NAP-GSP)**, a project of the UNEP and funded by the Global Environment Facility (GEF), assists least developed and developing countries identify technical, institutional and financial needs to integrate climate change adaptation into medium and long-term national planning and financing. Since 2016, NAP-GSP has assisted 59 countries in four regions with the assistance of 21 partners. ituyytf
- **The Green Climate Fund (GCF)** is accountable to the UN and operates under the principles of the UNFCCC. GFC has committed more than US$ 10 billion from 49 countries, regions and cities, leveraging US$ 37 billion with its co-funders. GCF provides support to developing countries for the formulation of NAPs and other adaptation efforts via its Readiness Programme. GCF operates a dashboard with detailed information about the more than 190 projects it has supported.

3.4.3. European Union Adaptation Guidance to Local and Regional Authorities

Over the last eight years, the EU has acted repeatedly to strengthen its commitment to limit global warming to 1.5°C, achieve Net Zero emissions, and adapt to the effects of climate change. The EU's commitment is codified in the European Green Deal, the European Climate Pact and its implementing Regulation on Governance of the Energy Union and Climate Action, the Action Plan for Financing Sustainable Growth, the Taxonomy for sustainable investments, its carbon credit trading market, the Green Bond Standard, and substantial appropriations for mitigation and adaptation efforts from the European Parliament. With this substantial commitment to public policy and finance, the EU Commission for the Environment, Climate Change and Energy set out an Adaptation guide for EU local and regional government authorities (LRAs). This guide was based on a literature review and a survey of stakeholders within LRAs.

Four key challenges emerged from this review:

- Lack of political leadership and commitment to adaptation;
- Insufficient administrative capacity;
- Insufficient financial resources; and
- Knowledge gaps. The lack of commitment to adapting to climate change as a political priority across all levels of government was identified as an overarching challenge by survey respondents.

A 2012 estimate of the economic, environmental and social costs incurred by inaction to the adaptation agenda would be high (€100 billion), and higher if delayed €250 billion). The EU Adaptation Strategy of 2013 sought to prepare the continent for the impacts of climate change. The Strategy was subject of an evaluation in 2018, which assessed the relevance, effectiveness, efficiency, coherence and "EU added value" of the Strategy. The evaluation found that adaptation measures were on the whole inadequately provided by Member States in their National Energy and Climate Plans (NECPs), which in which Mitigation measures predominated. Adaptation actions evaluated are summarized in the following table:

Actions of the EU Adaptation Strategy

Promoting action by Member States
Action 1: Encourage all Member States to adopt comprehensive adaptation strategies
Action 2: Provide LIFE funding to support capacity building and step up adaptation action in Europe
Action 3: Introduce adaptation in the Covenant of Mayors framework
Better informed decision-making
Action 4: Bridge the knowledge gap
Action 5: Further develop Climate-ADAPT as the 'one-stop shop' for adaptation information in Europe
Climate-proofing EU action: promoting adaptation in key vulnerable sectors
Action 6: Facilitate the climate-proofing of the Common Agricultural Policy, the Cohesion Policy and the Common Fisheries Policy
Action 7: Ensuring more resilient infrastructure
Action 8: Promote insurance and other financial products for resilient investment and business decisions

Source: EU Adaptation Strategy.

In an effort to focus investment on beneficial Mitigation and Adaptation measures, the EU published its Taxonomy for sustainable development. The taxonomy is a classification system which establishes a list of environmentally sustainable economic activities. This classification system is intended to provide project sponsors (including LRAs undertaking adaptation projects), investors, lenders, companies and policy makers) security from greenwashing, confidence in the mitigation and adaptation value of investments, and help drive investment to where it is most beneficial. The LRA Guide encourages LRA officials to use the Taxonomy to qualify their projects to leverage private sector capital.

The Guide focuses its recommendations for the Adaptation activities of LRAs in response to the four areas most needed, based on its survey of practitioners:

- Promote the mainstreaming of adaption across policies and all levels of governance;
- Develop the administrative capacity of LRAs to implement adaptation measures;
- Ensure climate finance is available for investing in adaptation; and
- Fill in the knowledge gaps related to adaptation.

This work is complemented by activities and resources of the European Climate Adaptation Platform Climate-ADAPT (Climate ADAPT EU), a partnership between the European Commission and the European Environment Agency (EEA). It provides stakeholders with resources, data and information sharing on:

- Climate change scenarios;
- Current and projected vulnerabilities for regions and sectors;
- Adaptation strategies across government levels;
- Case studies; and
- Planning tools.

Climate-ADAPT's website provides a database, which of information, which has been vetted, in the following areas:

- EU Policy: EU Adaptation Policy, Adaptation in EU Policy Sectors (Agriculture, Biodiversity, Coastal Areas, Forestry, Water management, Marine and fisheries, Ecosystem-based Approaches, Disaster Risk Reduction, Buildings, Energy, Transport, Health, Urban);
- EU Regional Policy;
- Countries, Transnational Regions, Cities;
- Knowledge: Topics, Data and Indicators, Research and Innovation projects, Tools, Practice;
- European Climate and Health Observatory "Knowledge"); and
- Networks.

The EU also operates, under the European Climate Infrastructure and Environment Executive Agency a funding program for the environment and climate action, where project sponsors can solicit technical assistance and financial support (EU LIFE Programme). Program areas include nature and biodiversity, circular economy and quality of life, climate change mitigation and adaptation, clean energy transition, and a portal for proposals and assistance for applicants.

3.4.4. Climate Adaptation Summit 2021 Priority Actions

CAS21, hosted by the Netherlands and sponsored by the UN, framed an Action Agenda for adaptation with a focus on measures needed this decade. The Summit mapped adaptation action areas in across four sectors, highlight three actions in each:

- Economy:
  - Optimize resilience of COVID stimulus funding
  - Invest in resilient infrastructure against compounding food-health-water crises, considering Nature-Based Solutions.
  - Support workforce protections.
- Food:
  - Develop local markets and value chains.
  - Promote resilient agriculture.
  - Build safety nets for food insecure households.
- Health:
  - Reinforce public health systems.
  - Promote systems that deliver health, economic and social co-benefits.
  - Leverage digital solutions for resilience in the face of food, health and climate-COVID risks.
- Water:
  - Promote best sanitation and hygiene practices.
  - Optimize water management.
  - Enhance water governance.

The Summit framed an adaptation action agenda more than it provided a resource for adaptation planning and execution. Nevertheless, it represented a powerful statement of the Adaptation agenda's importance. (It also served as a launch for the African Adaptation Acceleration Program mentioned above.

3.4.5. Global Commission on Adaptation 2021 Guidance on Key Sectors

Launched by the UN in 2018, GCA was charged by the leaders of 23 participating countries to accelerate adaptation, elevate its political visibility and identify concrete solutions. It concluded its charge with the Climate Adaptation Summit of 2021 profiled above. GCA published its flagship report Adapt Now: A Global Call for Leadership on Climate Resilience in 2019. It calls for actions in six key sectors, or systems. Excerpts from the Report below highlight the measures needed to accelerate climate Adaptation through 2030:

- **Food:**
  - Better align government finance and incentives for farmers with long-term, sustainable, "climate smart" production.
  - Dramatically increase access to information, innovative technologies, and finance to support the resilience for an estimated 500 million small-scale farming households.
  - Improve small farmers' productivity.

- Help small scale producers manage climate risks.
- Address the needs of the most vulnerable.
- Make smarter, climate-centered interventions in agriculture.

- **Natural Environment:**
  - Employ Nature-Based Solutions to regulate water flows, protect shorelines, cool cities, and complement built infrastructure.
  - Raise the understanding of the value of nature for climate adaptation.
  - Embed NBS solutions in adaptation policy and planning.
  - Accelerate political commitment, and enforcement, of habitat preserving commitments, such as the Convention on Biological Diversity.
  - Appropriately value natural assets in land use and investment decisions.
  - Recognize the mitigation co-benefits of many NBS adaptation measures.
- **Water:**
  - Invest in healthy watersheds and water infrastructure.
  - Improve efficiency and productivity of water use at all levels.
  - Integrate climate risks such as floods and drought at every level planning and operation.
  - Plan ahead for flood and drought.
  - Improve water governance and management.
- **Cities:**
  - Improve climate risk information and technical capacity, employing credible topographic, climate and community-level data.
  - Employ NBS solutions appropriate to the urban environment.
  - Upgrade the living conditions, and security, of nearly one billion people living in informal settlements who are particularly vulnerable to harm from climate change.
  - Capture value from adaptation benefits for community benefit. Link the preservation, and enhancement, of privately held (land) assets to value capture measures from land use and adaptation investments.
- **Infrastructure:**
  - Prepare financing (and insurance) in advance of disaster to minimize disruption when disaster damages infrastructure.
  - Recognize ports, roads, power, sanitation, sewer and communications systems as key infrastructure assets at risk from climate change.
  - Climate-proof existing infrastructure, and build new, resilient infrastructure. Mandate climate-resilient design.
  - Assets such as storm water management and measures protecting coastal communities against sea-level rise require public-private partnership and financing that share the costs, and the benefits, of these investments.

- Go beyond identification in individual assets to assure that entire systems are resilient, such as where and what to build, what to upgrade, and what to maintain and repair in the event of disaster.

- **Disaster Risk Management:**
  - Prepare people ahead of disasters to reduce loss of life from hurricanes, heatwaves, wildfire, floods.
  - Proactively move people, and assets, out of harm's way through better planning and investment decisions.
  - Assure social safety nets and improvements in forecasting help minimize loss and hasten recovery when they do strike.

It acknowledged overlap, or more appropriately, integration of measures across these sectors, and called for a seventh action area focused on expanding finance for adaptation:

- Shift how investment decisions are made by government, investors, and the nonprofit sector.
- Scale up and deploy public finance more effectively.
- Provide in advance adequate contingent financing and insurance to recover from disasters when they occur.
- Maximize opportunities for private capital investment, with appropriate risk-adjusted rates of return and loss mitigation.

CGA assembled an impressive list of partners, numbering nearly 100 organizations, which provided technical guidance and mobilized financial other resources to advance each of these sever "Action Tracks". The list is a useful resource and can be found on pages 68-69 of the Report, cited above.

3.4.6. World Bank Adaptation Principles

In 2020 the World Bank published its guide for ministries of finance and economy, and related partners such as multinational development banks (MDBs), DFIs and others. While the Annexes to the report offer helpful lists "indicators" for actions and policy priorities, overall the Guide's recommendations are broad and lack actionable programs and strategies. Nevertheless, it contributes to the important perspective of finance and economy ministries tasked with overseeing how adaptation (and mitigation) efforts are funded, and how they support local and state economic development. For the land policy perspective, the World Bank reaffirms the need expressed by others to adapt land use plans, protect critical public assets and services, inform land use and urban plans with climate risk assessment, and design and carry out government-wide strategies to increase the resilience of public assets and infrastructure.

Importantly, the Bank acknowledges that land markets often fail to incorporate climate risk assessment in valuations. It recognizes that is some countries land markets are outright dysfunctional, relegating hundreds of millions of people to life in informal settlements, with dangerously inadequate provision of services, and little to no land use or urban planning. Local and state officials are urged to incorporate climate hazard maps in location choices for investments in power, water, sanitation and transit infrastructure, and to guide spatial development, influence land use and intensity, land values, empowerment and population densities. The guide provides a Toolbox of suggested approaches, including map resources from NASA, MODIS Imagery and OpenStreetMap for road infrastructure.

The Bank recognizes the transformative role governments plays in transforming key assets for climate resilience: public assets and infrastructure systems such as power, roads, water and sanitation, and essential services including health care, education, safety and security. Urban and land use plans guide massive private investments in housing and other productive assets, particularly those that are land-based. Accordingly, it remains vital that land use planning respond to long-term climate risks, and avoid locking people into high-risk areas.

The costs of negligence are high. The Bank estimates that infrastructure disruptions in developing countries alone to annually cost enterprise US$300 billion and households US$90 billion. Using "the right data, risk models, and decision-making methods available, the Bank estimates the incremental cost of building resilient infrastructure is small: 3 percent of investment needs (no cite is offered). The principal challenge for resilient infrastructure is not primarily financing. Rather, resilient systems and assets will result from sound governance, decision-making, design, operations and maintenance. For example, "baking in" design which is resilient to climate risks upfront represents a small upfront cost with long-term dividends.

Perhaps one of the most important contributions of the World Bank Guide is the framework to manage financial and macro fiscal issues with respect to adaptation planning, finance and investment. Impact on GDP, trade balance and inflation are discussed. The Bank highlights the risk to asset valuations from the effects of climate change, and resultant impact on fiscal integrity of government finance which relies on those valuations (e.g., property taxes, export tax revenue falling $1.5 billion in Argentina in reaction to the severe drought of 2017).

The Bank calls for including contingent liabilities from natural disasters and environmental shocks in government planning and budgeting. It calls for developing a financial strategy to manage such contingent liabilities, using a diverse tool kit of financial instruments. These include contingent credit lines, insurance and catastrophe bonds, regional risk-sharing faciliti4sw, state contingent debt instruments and international aid. A combination of such tools will likely be needed to address the outsized capital needs caused by recurrent and increasingly severe disasters. Financial tools will be needed to cover both short-term liquidity challenges post-disaster, and longer term for repair, recovery and capital reconstruction.

The Bank urges governments play a proactive role in communicating and mitigating disaster and climate risk exposure of the financial sector and pension systems. It notes four climate-related risks to the financial sector:

- Operational risk: damage to financial infrastructure;
- Market and liquidity risk: "brutal" changes in asset valuations;
- Credit risk: shocks that damage borrower repayment ability and lower collateral prices; and
- Underwriting risk: errors in pricing of (re)insurance liabilities.

In calling for the allocation of adequate funding for an Adaptation strategy, the Bank notes that a "small dedicated adaptation budget" may be needed. However, integrating adaptation and resilience funding into sectoral budgets for key infrastructure, public assets and services will likely be required.

3.4.7. C40 Cities/McKinsey Sustainability

C40 Cities, a global network of mayors committed to action on climate change, together with the McKinsey Sustainability, published its report in 2021: Focused Adaptation: A Strategic Approach to Climate Adaptation in Cities. Noting that cities on the front lines of impacts from climate changes and the urgent need to adapt to those impacts:

> Hundreds of millions of people could suffer lethal heat waves in India, floods in Vietnam's Ho Chi Minh City could result in losses of billions of dollars, and home in Florida could $30 billion to $80 billion in value. The imperative is to act—and to start now.
>
> C40 Cities, McKinsey Sustainability, 2021

This report represents an effort to guide city policy makers and stakeholders through the extreme complexity of urban systems, conditions and various exposure to climate risks. These complexities include widely divergent economies, populations, geographies, access to natural resources and environments, and various social, cultural, institutional and built environment assets of cities. Other variables include topography, soil conditions, elevation, latitude, composition of power supply and the power grid, age and condition of buildings, degree of informal settlements and more. Adaptation strategies that may be available to some cities are not for others, or are simply inappropriate to their circumstances. The report notes city policy makers and stakeholders confront "a dizzying array of options for adaptation, making it difficult to set priorities and choose a course of action."

The Report attempts to offer city leaders a starting point for considering adaptation measures. Fifteen "high-potential" actions are described. These were developed by authors with consideration for risk-reduction potential, cost, feasibility and stakeholder complexity. Four of these actions build systemic resilience, and may be applied to all cities, regardless of their circumstance. Eleven actions respond to five specific types of hazards:

- Extreme heat;
- Inland flooding;
- Coastal flooding and storm surges;
- Drought; and
- Wildfires.

Several themes are identified across all these measures. First, nature-based solutions (NBS) offer among the most attractive actions for their potential for risk reduction and their feasibility. Examples include planting trees, using natural urban drainage solutions, creating natural coastal barriers, and managing river catchment areas for flooding and ground water recharge. Many of these measures share co-benefits with mitigation, economic development and health.

Second, as with the World Bank's admonition, cities should invest in resilience systematically, not simply in response to immediate, specific hazards such as hurricanes or floods. Such an urban, systematic approach to adaptation includes offering leadership to increase awareness of climate risks, incorporating risk assessment in all city planning, optimizing emergency response and warning, and enhancing financial and insurance programs to respond as required.

The Report provides a "pathway" for urban policy makers for successful implementation of the suite of adaptation measures best suited to a city's unique risks, assets and conditions. A summary of the steps for this pathway includes:

- Conduct a risk assessment;
- Create a list of existing and potential adaptation actions;
- Conduct benefit and feasibility analyses on each proposed action; and
- Create a cohesive plan.

To be effective, city leaders should incorporate the following five practices in crafting and carrying out their adaptation measures:

- Governance: integrate adaptation decision making, planning and execution into charters, agency mission statements, staffing and budgeting, and stakeholder involvement.
- Strategic Planning: Monitor, evaluate and amend climate adaptation measures as needed on a regular, incorporated in city budgeting, capital planning and long-range planning (land use plans, operations and maintenance schedules, fiscal analysis).
- Monitoring and Reporting: establish key performance indicators, monitor and publicly report progress in transparent fashion.
- Capacity Building and Stakeholder Management: seek assistance from partners in the private sector, community organizations, academic institutions. Build public awareness campaigns. Actively seek broad-based, continuing engagement of all stakeholder groups in planning, assessing and carrying out adaptation measures.
- Financing: Adaptation requires investment. Cities will need to reflect adequate financing, to the extent of their fiscal capacity, in their budgeting and public finance activities. Given the fiscal limits on cities, they will need to seek leverage from other partners. These include state and national agencies, as well as private sector partners, including public-private partnerships, green bonds, insurance, risk reduction structures and other financial mechanisms.

Following is a summary of the eleven actions, organized by specific climate threats, which the Report characterized as "high-potential" when measured by effectiveness, efficiency and capacity to deliver co-benefits:

Heat

- Street Trees: Planting trees and local species reduces heat at street level.
- Cool Surface Treatments: Solar-reflective "cool" pavements mitigate urban heat-island effects. "Cool" roofs reduce conduction of heat into buildings, convection of heat into the outside air, and thermal radiation of heat into the atmosphere.

Inland Flooding

- Nature-based sustainable urban drainage solutions (SUDS). Reducing paved spaces increase the grounds ability to absorb rainwater. Rain gardens pool rainwater and enable it to soak into the ground. Bioswales channel storm water runoff, control pollution, and restore groundwater.
- River-catchment management: Protecting upriver catchment areas and river basins leverages the natural ecosystem's ability to absorb and filtrate

water; a holistic approach may include considering downstream drainage such as expanding natural river banks.

Coastal Flooding and Storm Surges

- Investing in flood- and storm-resilient buildings. Building features such as dry-proofing and wet-proofing reduce flood damage; wet-proofing reduces interior damage by designing basements with flood openings and moving critical equipment such as boilers to upper floors. Elevated buildings are less likely to be damaged by flooding.
- Coastal Artificial Barriers: Seawalls, in addition to barriers such as floodgates, breakwaters, sandbags, and revetments, prevent flooding. Groynes are human-made structures that interrupt waves, thereby reducing sediment erosion.
- Nature-based Solutions: Mangroves restoration.

Drought

- Efficiency Improvements: Smart technology, such as sensors on water pipelines, helps system operators identify and fix leaks quickly. New water infrastructure reduces leaks, thereby increasing water system throughput.
- Behavioral-change programs: Public outreach, such as how to conserve water and communications to increase awareness of drought, can reduce water consumption.

Wildfire

- Development Planning: Planning to reduce the building of homes and communities wildfire-prone areas while creating ignition-resistant building codes for new developments reduces the impact of fire risk.
- Preventive forestry management: Fuel breaks such as cleared parts of forests or roads help control, and possibly stop, the spread of wildfires. Prescribed and controlled burns consume organic material (e.g., leaves and branches), reducing fuel for wildfires.

C40 Cities, McKinsey Sustainability, op cit

4. CAPITAL REQUIREMENTS

The capital requirements to achieve Net Zero 2050 call for the mobilization of public and private capital at unprecedented global scale and speed.

IEA's Roadmap to Net Zero by 2050 for the global energy sector, the Network for Greening the Financial System (NGFS), the International Renewable Energy Agency (IRENA), and BloombergNEF variously estimate the capital requirements to achieve 1.5°C by 2050 from $100 trillion to $150 trillion. While this may seem a daunting figure, it is achievable. Spread over the next 30 years, even at the upper range this number represents less than 5% of global GDP ($84.7 trillion in 2020, down due to the pandemic from $87.5 trillion in 2019). Global GDP in 2021 is estimated at $94 trillion.

The UN's Race to Zero "Net Zero Financing Roadmaps" report provides an interactive tool which lays out the scale and pace of capital investment required to transition the global economy to Net Zero by 2050, by economic sector, by region, and by country.

Coming out of COP 26, the Glasgow Financial Alliance for Net Zero (GFANZ) announced a pledge of more than $130 trillion in private capital commitments to help achieve Net Zero 2050. With its focus on the mobilization of private capital, the GFANZ announcement is coupled with needed market improvements to:

- standardize reporting for climate metrics and financial accounting;
- manage risks of climate investment and climate-induced risks (and benefits) to assets and portfolios;
- rationalize returns on a risk-adjusted basis, and
- promote public-private sector partnerships and regulation.

Several financial industry alliances support the GFANZ pledge:

- Net Zero Asset Owner Alliance
- Net Zero Banking Alliance
- Net Zero Insurance Alliance
- Net Zero Asset Managers Alliance
- Net Zero Financial Service Providers Alliance
- Paris Aligned Investment Initiative (PAII)

The UN published its strategy to build a private finance system for Net Zero 2050.

The Climate Policy Initiative (CPI) reported that "total climate finance" reached $632 billion over the two year period 2019/2020, and that an increase of nearly 600% in annual climate finance is required for a Net Zero path by 2030. Adaptation finance represented a mere 7% of total climate finance. CPI's Framework for Sustainable Finance Integrity proposes actions required to meet global climate finance requirements.

The IEA's Net Zero 2050 Roadmap for the energy sector quantifies investment requirements by sector (energy, transport, buildings, manufacturing, agriculture), by region and by country. It provides an interactive tool to trace investment and emission targets.

The European Union published its Green Bond Standard in July, 2021. Derived from the EU's 2018 action plan on financing sustainable growth, the Green Bond Standard establishes a common framework throughout the EU for issuers, investors and project sponsors, providing for large scale investment in sustainable development projects consistent with the EU's own Net Zero 2050 ambitions. The Green Bond Standard aligns with the EU's Taxonomy for sustainable development activity, as certified by external review, and to assure full transparency through robust reporting requirements, all under the registration and supervision of the European Securities Markets Authority (ESMA).

Capital market participants will look for continued clarity, transparency, security and liquidity in the definition of "green investment", and the EU's Green Bond Standard provides an excellent starting point.

Carbon Trading Markets

For more than fifteen years, various markets have been established, both government-regulated and voluntary among enterprises, to trade "carbon credits." Under such systems, one enterprise's GHG emissions falling below a regulated or voluntary cap, may be "sold" to another enterprise whose emissions exceed such caps ("Cap and Trade").

The European Union Emissions Trading System (ETS) was the first international carbon credit trading market, established in 2005. ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the entities covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, entities buy or receive emissions allowances, which they can trade as needed. The limit on the total number of allowances available ensures that they have a value. After each year, an installation must surrender enough allowances to cover fully its emissions, otherwise heavy fines are imposed. If an installation reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another installation that is short of allowances. (Ibid) The EU seeks to link the ETS with other compatible systems. For example, a bilateral ETS agreement has been developed with China.

"Compliance Carbon Markets" (CCMs), that is those sanctioned by government regulation, exist in California (2013), Japan, China, New Zealand, South Korea, Switzerland and Canada, and as noted in the EU. Voluntary Carbon Markets (VCMs) have proliferated independent of government-sanctioned CCMs. The value of the four largest ETSs in 2020 was $100 billion. Estimates of the scale of VCMs by 2030 vary widely, from $5 billion to $180 billion. Relative to the scale of capital required for Net Zero 2050, carbon markets are still quite small. They also pale in comparison to the global environmental cost of fossil fuels, which the IMF estimated at $5.9 trillion in 2020, or 6.8% of global GDP. The IMF forecasts this to grow to 7.9% of global GDP by 2025.

Critics of carbon market schemes claim they place no restraint on emissions, and simply allow emitters to continue with their operations, while adding an incremental cost of doing business. As the IMF demonstrates, these markets come nowhere close to the scale of the cost of carbon.

Nevertheless, interest in CCMs and VCMs continues, and resulted in a notable outcome from Glasgow, with the endorsement of the first set of preliminary rules governing how governments and companies create, value and swap credits in an effort to lower emissions. While no enforcement mechanism was established, the UN agreement calls for establishing a global supervisory body to oversee the marketplace. Nominations are invited for the body, which will meet semi-annually, and which will be tasked with developing technical methods, registration and monitoring processes.

5. CLIMATE CHANGE CAPITAL RISKS AND OPPORTUNITIES TO LAND-BASED ASSETS

In the spring of 2021 the People's Bank of China and the IMF sponsored a high-level seminar on green finance and climate policy. The PBC and IMF noted:

> "Climate change poses a fundamental risk to economic and financial stability. But tackling climate change also provides an opportunity to reinvigorate growth, create new jobs, and secure a green recovery at a critical moment. Climate change poses challenges for central banks, for monetary policy, and for financial stability. The financial industry will both be affected by climate change and help facilitate strong adaptation and mitigation polices. Here, central banks and financial supervisors can play a crucial role—including by assessing risks, stress testing, and establishing transparent regulatory frameworks around the financing of "green" investment."
> PBC, IMF, op cit

Financial regulators, industry groups and third party institutions across the world are hard at work to craft common, measurable indicators of risk, and opportunity, for every class of financial asset: loans, investments, securities, businesses, insurance, assets under management.

The European Union has adopted perhaps the most advanced protocols for identifying "green" and "brown" investments held by financial institutions. The EU Taxonomy, codified in adopted law and regulation (see below), is a detailed classification system, establishing a list of environmentally sustainable economic activities in each sector.

The Taxonomy Regulation establishes six environmental objectives:

1. Climate change mitigation
2. Climate change adaptation
3. The sustainable use and protection of water and marine resources
4. The transition to a circular economy
5. Pollution prevention and control
6. Protection of biodiversity and ecosystem

The Regulation requires disclosure of investments in the following sectors:

- Agriculture, forestry and fishing
- Manufacturing
- Electricity, gas, steam and air conditioning supply

- Water, sewerage, waste and the related remediation
- Transportation and storage
- Information and Communication Technologies (ICT)
- Buildings (construction and real estate activities, with application to other sectors where appropriate).

The EU Taxonomy Delegated Act contains the technical screening criteria ("TSC") for climate change adaptation and mitigation under the EU Taxonomy Regulation. The Taxonomy is geared to lead Europe to a Net Zero economy by 2050. It is supported by several fiscal measures and strategies, including the EU Green Deal and, in the case of buildings, the EU Renovation Wave Strategy.

In the United States, President Biden issued an Executive Order on Climate-Related Financial Risks with wide reach into the range of federal finance policy and regulation. Gary Gensler, the Chairman of the US Securities and Exchange Commission (SEC), has solicited public comment on the disclosure of climate-related risks to publicly traded companies, and reports that three fourths of comments received supported some regimen of public disclosure. On March 21, 2022, the SEC published its Proposed Rule for disclosure of climate-related risks by regulated entities. US Treasury Secretary Janet Yellen in remarks before the Financial Stability Oversight Committee (FSOC) that "climate change is an emerging and increasing threat to U.S. financial stability".

President Biden's Assistant Secretary for Financial Institutions at Treasury, Graham Steele, has called for the regulation of systemically important financial institutions' SIFIs) investments which contribute to climate change—from fossil fuels to deforestation—and thereby create systemic risk. Such regulation may include:

- Setting rules for risk-based capital;
- Conducting stress tests tied to climate-related risks;
- Limiting margin, that is, the posting of assets for securities transactions, when those assets, or securities, contribute to global warming;
- Limiting loan and investment portfolio exposure to climate change-related assets;
- Requiring divestiture of climate change-causing assets.

Within the US insurance industry, a request for comment from the Federal Insurance Office (FIO) has sparked the concerns regarding federal oversight of the current state-based system of insurance regulation. President Joe Biden in an executive order tasked FIO with assessing "climate-related issues or gaps in the supervision and regulation of insurers" and examining the prospects of "major disruptions" of private insurance coverage in parts of the U.S. that are particularly vulnerable to the impacts of climate change.

Among industry, intermediary and nonprofit organizations, multiple efforts have emerged to define, quantify, measure, disclose, understand and regulate climate risks to the entire range of financial assets and institutions.

CDP, the Climate Disclosure Standards Board (CDSB), the Global Reporting Initiative (GRI), the International Integrated Reporting Council (IIRC) and the Sustainability Accounting Standards Board (SASB) jointly published a financial disclosure standard to measure climate risks and benefits to financial assets and activity.

The Task Force on Climate-related Financial Disclosures (TCFD), led by Michael Bloomberg, developed guidance on climate-related metrics, targets and transition plans for companies

The OECD warns that "climate change is expected to affect the fiscal sustainability of government budgets in the medium and long term."

S&P, Moody's and Fitch have all issued guidance threatening downgraded credit ratings for states and municipalities particularly exposed to the damaging effects of climate change. Researchers Linda Shi and Andrew Veruzzo found from an examination of 99 coastal municipalities in Massachusetts:

- Sea level rise will decrease property tax revenues significantly in some coastal cities
- Cities are putting major developments on waterfronts to maximize tax revenues despite known flood risks
- Affected cities have limited spatial, developmental, and fiscal capacity to overcome climate-driven fiscal gaps
- Fiscalization of land use is a barrier to effective long-term climate adaptation

Utilities, both publicly traded and government-owned, face enormous financial costs is adapting to climate change, and converting to renewable generation, storage and distribution. The largest publicly-owned utility in the United States, PG&E, was forced into bankruptcy over civil penalties levied as a result of wildfires sparked by its power lines. It is now seeking to permission from the California Public Utility Commission to raise customer rates, already among the highest in the country, 18% in 2023. The company estimates that it will cost $15 billion to $20 billion to underground its powerlines throughout forestlands throughout its 70,000 square mile service territory, across more than 100,000 miles of transmission lines. In Texas, estimates of the costs to winterize the grid against the kind of failure experienced in the winter of 2021, affecting some 10 million residents, range from $5 billion to $20 billion.