

ICEF Innovation Roadmap Project



7TH ANNIVERSARY EDITION

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We dedicate this booklet to the memory of Prime Minister

Shinzo Abe, founder of ICEF



It is my honor to dedicate this booklet to Primer Minister Shinzo Abe, the founder of the Innovation for Cool Earth Forum (ICEF). Prime Minister Abe's vision led to the creation of ICEF, and his support helped turn it into a leading global conference. His dedication in helping lead Japan and the world in the fight against climate change will have a lasting impact. He is a rare political leader with global identity. We miss him a lot.

At ICEF, leaders from around the world gather each year to discuss priorities in moving the world toward net zero emissions. Each year we celebrate leading innovations with the potential to contribute to that goal, both in the short- and long-term. And each year we release at least one innovation roadmap charting a path forward for technologies that can play an important role in the transition to a net zero world.

Since 2015, Innovation Roadmaps have been a core part of ICEF. The roadmaps have covered a wide range of topics including carbon dioxide utilization, zero emissions buildings, industrial decarbonization, direct air capture, biomass carbon removal and storage, carbon mineralization and more. They are rich in technical detail and filled with important recommendations for policy makers around the world. These Innovation Roadmaps are released in draft at the ICEF conference each year and in final at the annual Conference of the Parties to the UN Framework Convention on Climate Change.

I'd like to warmly thank David Sandalow for his leadership of the ICEF Innovation Roadmap Project. With his support, ICEF has produced roadmaps that have had a significant impact and won widespread praise.

Thank you for your interest in ICEF and the ICEF Innovation Roadmap Project. We hope to see you in Tokyo in the years ahead.

Nobuo Tanaka
Chair, ICEF



During the summer of 2022, extraordinary heat waves swept the globe.

In June, Japan suffered through its worst heat wave ever, with temperatures of more than 35°C (95°F) in Tokyo for eight straight days. In July, the United Kingdom endured its hottest days ever, with temperatures in London exceeding 40°C (104°F) for the first time. For 10 weeks from the middle of June through the end of August, China saw its worst heat wave ever, with hundreds of temperature records broken across many parts of the country.

In Europe, the United States and China, rivers ran dry. At the same time, consistent with the warnings of scientists who tell us that global warming will bring more droughts and more floods, unprecedented rain fell in some regions. At the end of August almost a third of Pakistan was underwater as a result of monsoon rains carrying three times more water than average.

This is a vision of our future unless the world stops pouring more and more heat-trapping gases into the atmosphere each year.

There are many signs of hope. Solar power costs have fallen 90% in the past decade. Wind power costs have fallen by two-thirds. Li-ion battery costs have fallen by half. Investment capital is flowing into low-carbon hydrogen projects. The first direct air capture facilities are now operating, with more under development.

Around the world, many heads of state and other political leaders are mobilizing to fight climate change. Businesses are investing hundreds of billions of dollars in the clean energy transition. Universities are updating their curricula to help train new generations of climate leaders. Youth movements are calling for dramatic changes.

For the past seven years, it has been my great privilege to lead the ICEF Innovation Roadmap Project’s work to help chart a path towards a better climate future. I’m hugely grateful for the brilliance, expertise and camaraderie of distinguished co-authors and deep commitment of ICEF leadership to our work. I hope the ICEF Innovation Roadmaps provide insights into promising technologies for the fight against climate change and help move us toward a world with net zero emissions.

David Sandalow
Chair, ICEF Innovation Roadmap Project



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Low-Carbon Ammonia Roadmap



Low-Carbon Ammonia Roadmap



Ammonia (NH_3) is one of the building blocks of modern society. By one estimate, only half of the current global population could be fed without ammonia, which is used to make fertilizers. Ammonia is also used in the manufacture of plastics, rubber, fibers and explosives.

Almost 2% of global CO_2 emissions come from the production of ammonia. Most of these emissions come from separating hydrogen from natural gas or coal. These emissions could be reduced or eliminated with low-carbon alternatives. The leading options are (i) capturing the CO_2 emitted in these processes and storing that CO_2 underground or in long-lived products, and (ii) separating hydrogen from water using electricity from zero-carbon sources.

Low-carbon ammonia could then be used to substitute for carbon-intensive fuels or as a store of surplus renewable power, providing significant additional emissions reductions

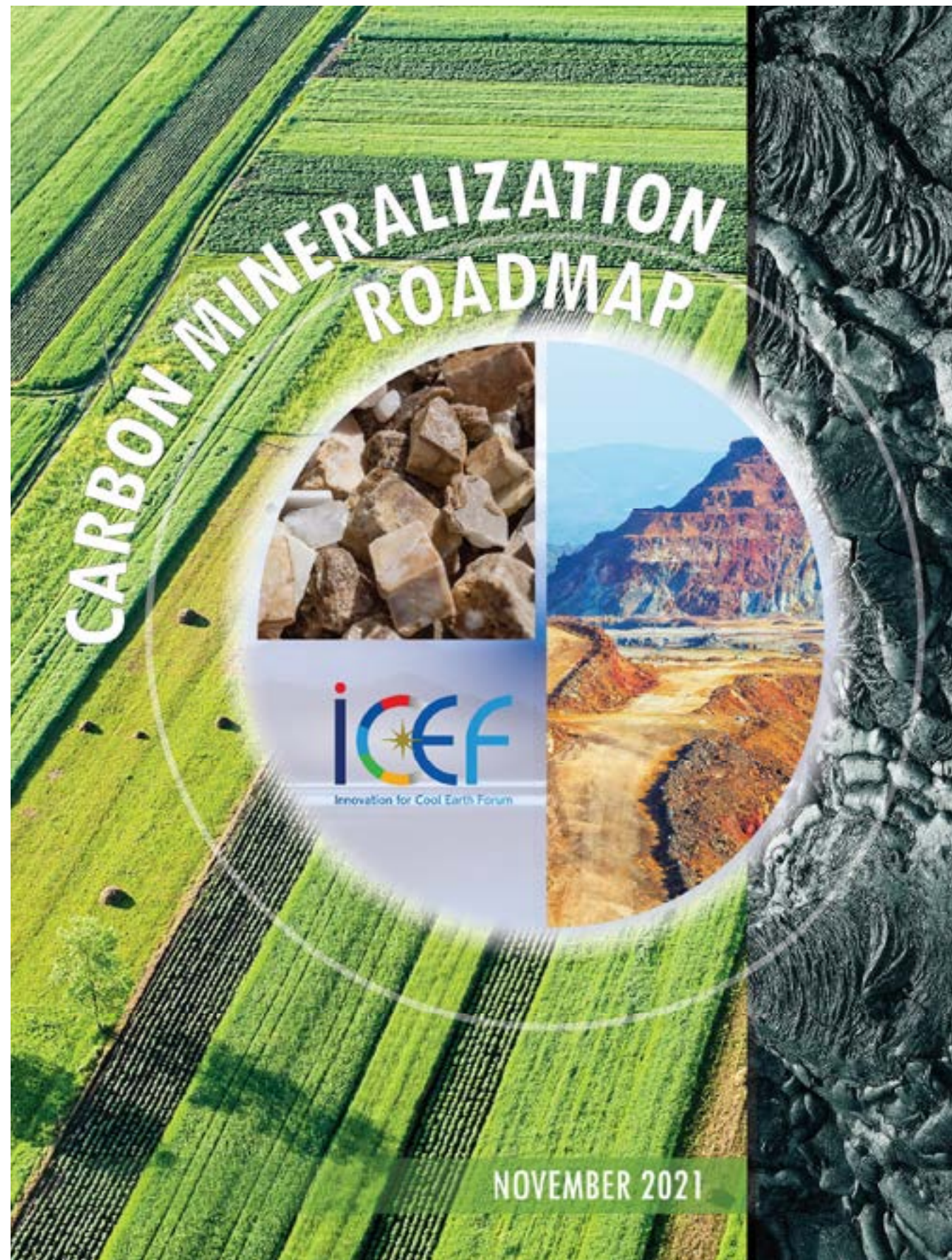
This roadmap explores a range of topics related to low-carbon ammonia. The roadmap examines the global ammonia industry today, strategies for reducing the cost of low-carbon ammonia production, infrastructure needs for scaling up low-carbon ammonia, different ways that low-carbon ammonia could be used to reduce emissions in the years ahead, the safety and local environmental impacts of expanding ammonia production and use, R&D needs and policy options.

The roadmap finds that low-carbon ammonia could produce substantial greenhouse gas reductions in key sectors this decade and significant reductions in many sectors by 2050. Its recommendations include: (i) governments should launch public-private partnerships to plan, develop and finance infrastructure for low-carbon ammonia, and (ii) policy incentives to bring ammonia production, transportation and use to the market should be based on carbon intensity.

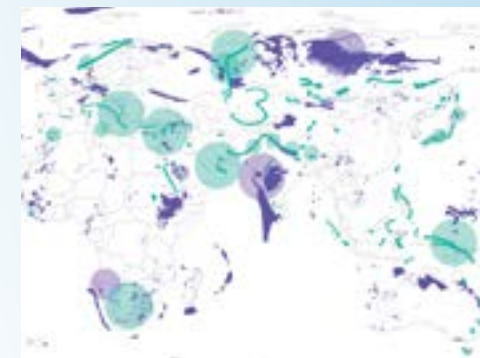
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A draft of the ICEF Low-Carbon Ammonia Roadmap can be found at <https://www.icef.go.jp/roadmap/>.



Carbon Mineralization Roadmap



Carbon mineralization is a natural process in which carbon dioxide (CO₂) becomes bound in rocks as a solid mineral, permanently removing the CO₂ from the atmosphere. This process could provide the foundation for a range of activities that not only help fight climate change, but create jobs and deliver local environmental benefits as well. Resources for carbon mineralization are abundant and located in dozens of countries around the world.



There are two broad approaches to increasing the amount of CO₂ removed from the atmosphere via carbon mineralization: injecting CO₂-rich fluids into rock formations deep underground (in situ mineralization) and exposing crushed rocks on the Earth's surface to CO₂-bearing gases (ex situ or surficial mineralization).

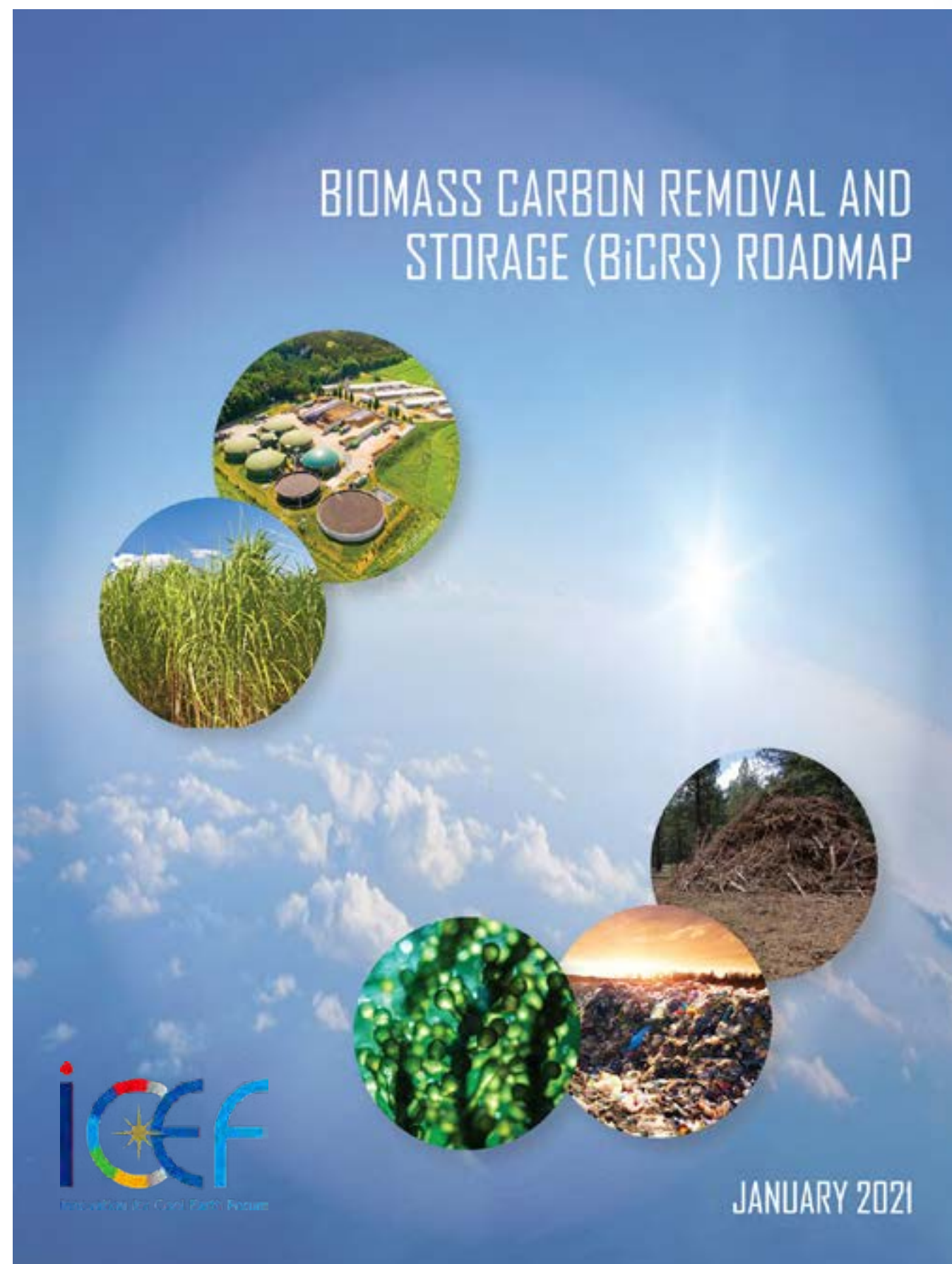
As a strategy for CO₂ removal and sequestration, carbon mineralization has both strengths and weaknesses. Mineralization resources are effectively unlimited and located in dozens of countries around the world, and mineralization offers one of the most permanent forms of CO₂ sequestration available, binding CO₂ into solid rock. However, natural carbon mineralization happens very slowly, and the commercial value of mineralization products are typically low.

The authors estimate that, with strong and sustained policy support from governments around the world, carbon mineralization processes could remove 1 GtCO₂ from the atmosphere per year by 2035 and 10 GtCO₂ per year by 2050. However policymakers have paid scant attention to carbon mineralization as a strategy for helping achieve net zero emissions. This ICEF Roadmap provides basic background on carbon mineralization, suggests a research agenda and proposes policies to help carbon mineralization achieve its potential in fighting climate change.

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The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2021_roadmap.pdf



Biomass Carbon Removal and Storage (BiCRS) Roadmap



This roadmap introduces a new term: biomass carbon removal and storage (BiCRS). The term describes a range of processes that use plants and algae to remove carbon dioxide (CO₂) from the atmosphere and store that CO₂ underground or in long-lived products.

The authors believe the term “bioenergy carbon capture and storage (BECCS)” is too limited and has the wrong emphasis. BECCS starts with the word “bioenergy,” but some processes that use biomass to remove CO₂ from the atmosphere do not involve bioenergy. Furthermore, when bioenergy and carbon capture are combined, the removal of CO₂ from the atmosphere will often be more valuable than the energy produced.

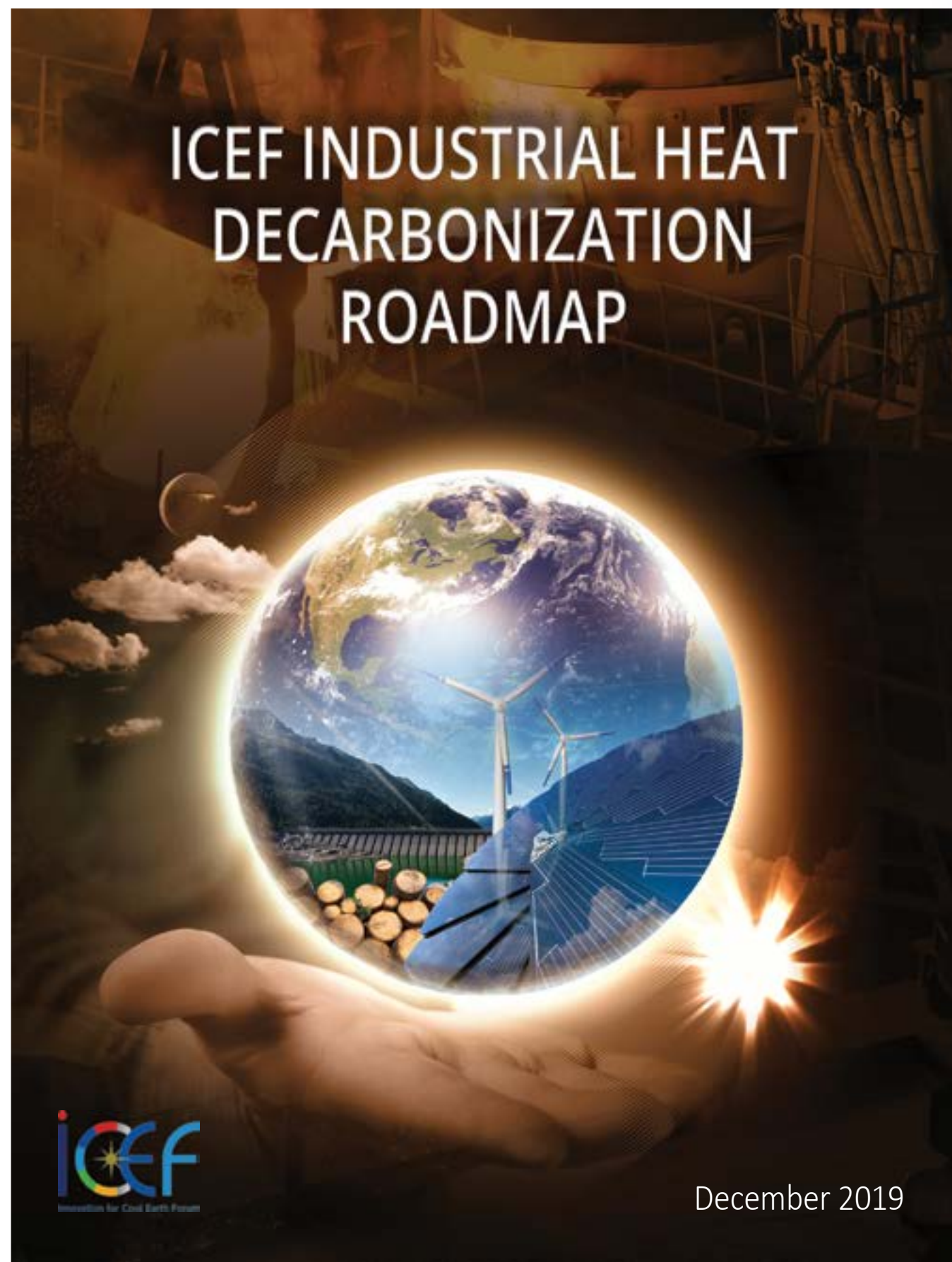
The use of biomass for climate mitigation has generated controversy for many years. Advocates point to potential benefits including cheap emissions reductions, biodiversity conservation and sustainable livelihoods. Critics point to risks including competition with food resources, indirect land use change that reduces or eliminates any climate benefits, and adverse impacts on rural communities.

This Roadmap finds that (i) several gigatons of CO₂ could be permanently removed from the atmosphere each year using BiCRS, (ii) many technologies and practices required for BiCRS are already mature and (iii) without proper governance and standards, BiCRS could be counterproductive. The Roadmap recommends (i) focusing on waste biomass as the initial feedstock for BiCRS project, and (ii) for all BiCRS projects, strict adherence to the guiding principle “Do no harm.”

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The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2020_roadmap.pdf



ICEF Industrial Heat Decarbonization Roadmap



Roughly 10% of global greenhouse gas (GHG) emissions come from the production of heat for industrial processes—more than cars and planes combined. Decarbonizing industrial heat production will be essential to meeting the Paris Agreement goals. This topic has received far less attention than decarbonization of the power, transport or building sectors.

Most heavy industries require enormous quantities of heat. Today, almost all industrial heat is provided by combustion of coal, oil or natural gas. These fossil fuels provide the high temperatures, continuous operation and reliability many industrial processes require. Any options for decarbonizing industrial heat must match these capabilities or be part of a broader change in industrial processes.

Options to provide low-carbon heat for industry include hydrogen; biomass; electrification; carbon capture, use and storage (CCUS); nuclear power; and concentrated solar power (CSP). Few if any of these options are well-developed in the context of industrial heat production. Key sectors include iron and steel, chemicals, and cement.

This roadmap finds that there are many pathways for reducing the cost and improving the performance of approaches to providing low-carbon industrial heat. The roadmap recommends that (i) this topic receive far greater attention in climate mitigation strategies, and (ii) governments implement policies to accelerate and support industrial decarbonization, including more research and development funding and “buy clean” procurement rules.

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The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2019_roadmap.pdf

Direct Air Capture of Carbon Dioxide


December 2018

ICEF Roadmap 2018

Direct Air Capture of Carbon Dioxide



Concentrations of carbon dioxide (CO₂) in the atmosphere have reached their highest levels in roughly three million years. Those concentrations continue to climb year after year. Dramatically cutting CO₂ emissions is essential, but not enough. The IPCC's *Global Warming of 1.5°C* report (2018) states that 100-1000 gigatons (Gt) of carbon dioxide removal will be needed this century to prevent global average temperatures from climbing 1.5°C (2.7°F) above pre-industrial levels.



Examples of CDR include afforestation, bioenergy with carbon capture and storage, and direct air capture of carbon dioxide (DAC). Atmospheric CO₂ scrubbers—DAC at a small scale—have been used in submarines since the 1940s and spaceships since the 1950s. The movie *Apollo 13* recounts a dramatic effort to design a CO₂ scrubber aboard a damaged spacecraft en route to the Moon.

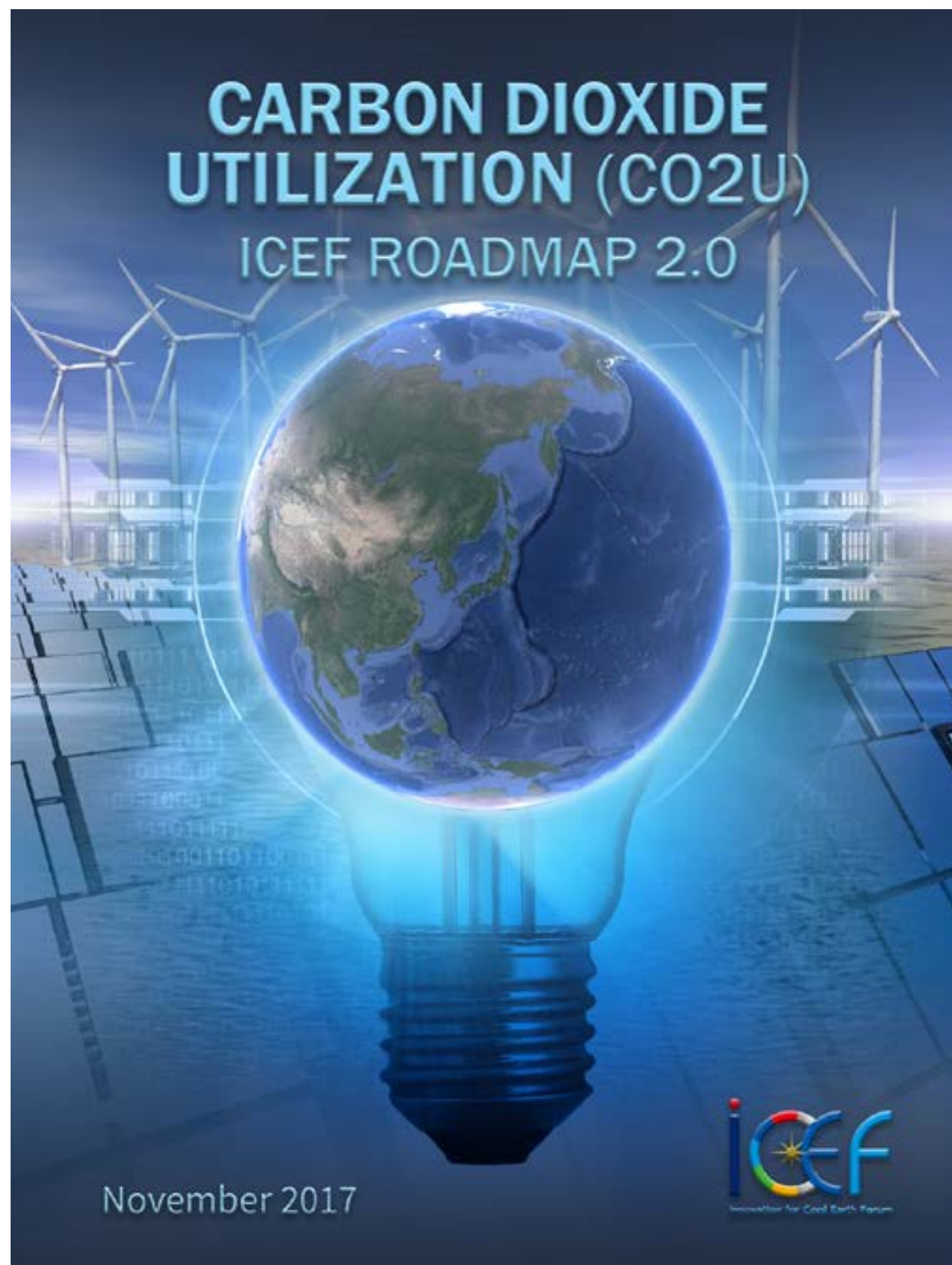
As a climate mitigation strategy, DAC has many advantages. It has a small physical footprint, uses earth-abundant materials. It removes CO₂ from the atmosphere in way that is easy to measure and clearly additional. The geological capacity to store CO₂ removed with DAC is essentially unlimited. However DAC is limited by high costs and the availability of carbon-free electricity and heat needed for DAC equipment.

This roadmap explores chemical, cryogenic and membrane DAC technologies. It recommends key areas for RD&D to advance DAC, including materials, low-carbon heat, air contactors, process designs and systems analysis. The roadmap recommends that governments promote DAC with research and development funding, procurement authorities, fiscal incentives and eligibility in emissions trading programs.

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The ICEF Carbon Mineralization Roadmap can be found at
https://www.icef.go.jp/pdf/summary/roadmap/icef2018_roadmap.pdf



Carbon Dioxide Utilization (CO₂U)



CO₂ utilization (CO₂U) is the utilization of CO₂ for a beneficial purpose. CO₂U can help offset the cost of carbon capture. It can also create products that displace fossil fuels and sequester CO₂ for the long-term. Traditionally, CO₂U has involved enhanced oil recovery, but increasingly it has focused on the conversion of CO₂ into products including synthetic fuels, plastics and cement.

CO₂U involves a wide array of applications, technologies, energy requirements and settings. The potential range of applications is very large, including greenhouses, organic farming, fuels, chemicals, long-lived solids (e.g., plastics, carbon fiber, graphene) and carbonate minerals. These products all have different price-points, market volumes, and performance requirements.

This roadmap explores technologies for converting CO₂ to into products, the potential market value of these products, associated research and development needs, life-cycle analyses and government policies to advance CO₂U. It includes case studies on cement and aggregates, chemical intermediates, and solid materials.

The roadmap finds that CO₂U can be an important tool for stimulating and revitalizing industries, creating jobs and delivering climate benefits. It explores life cycle analysis (LCA), concluding that considerably more work is needed on LCA methodologies. The roadmap recommends that government support CO₂U with tools including tax credits, subsidies and procurement mandates. Governments should also provide regulatory clarity through the adoption and use of LCA and product standards.

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The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2017_roadmap1.pdf



ENERGY STORAGE ROADMAP - TECHNOLOGY AND INSTITUTION –

November 2017

Energy Storage Roadmap



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Energy storage enhances energy system flexibility. It integrates variable renewable power into electric grids, improves resource efficiency, enables end-use electrification especially in transport, supports the production of energy where it is consumed, increases energy access and improves grid stability, flexibility, reliability and resilience. The International Energy Agency estimates that 1,365 GW of stationary energy storage and 28 TWh of electric vehicle batteries must be deployed by 2060 to achieve the 2°C scenario.

This ICEF roadmap focuses on three categories of energy storage; 1) stationary electric energy storage technology, 2) mobility electric energy storage technology, and 3) stationary thermal energy storage technology. This roadmap summarizes the current status of energy storage technologies in each of these categories and clarifies required R&D targets and support policies. The roadmap explores the following technologies:

Stationary Electric Energy Storage Technology—Pumped-Storage Hydropower, Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES), Superconducting Magnetic Energy Storage (SMES), Flywheel, Supercapacitor, Lead Acid Battery, Nickel-metal Hydride Battery, Lithium Ion Battery, Sodium Sulfur Battery (NAS Battery), Redox Flow Battery, All-solid-state Lithium Battery, Metal Air Battery, Power to X (X=Hydrogen, gas, etc.)

Battery Technologies for Electric Vehicles—Nickel-metal Hydride Battery, Lithium Ion Battery, All-solid-state Lithium Battery, Metal Air Battery, Electric Vehicle Chargers, Power to Grid

Stationary Thermal Energy Storage Technology—District Heating & Cooling (Ice Storage), Underground Storage, Pit Storage, Molten Salt, Thermochemical

The roadmap recommends:

- Creating new energy markets for stationary electric energy storage technology deployment,
- Developing high energy density batteries and wireless charging for electric vehicles deployment, and
- Promoting stationary thermal energy storage to utilize renewable-based or environmental heat.

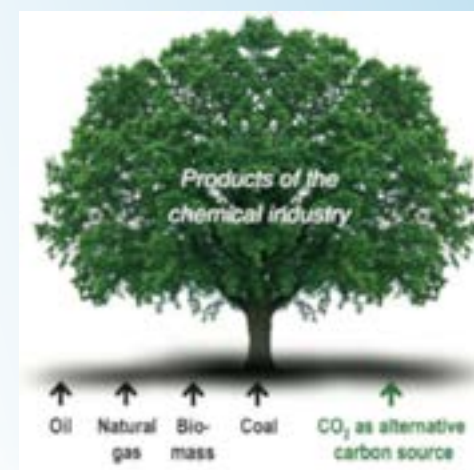
The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2017_roadmap2.pdf

CARBON DIOXIDE UTILIZATION (CO₂U) -- ICEF ROADMAP 1.0

NOVEMBER 2016



Carbon Dioxide Utilization (CO₂U)



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Carbon removal technologies (those that reduce atmospheric CO₂ concentrations) are needed to achieve the agreed global goal of limiting the increase in global average temperatures to well below 2°C over pre-industrial levels. Carbon dioxide utilization (CO₂U) technologies can play an important role, but their potential has not been explored in a comprehensive fashion. This roadmap explores the commercialization potential of CO₂U technologies through 2030.

This roadmap evaluates almost 180 CO₂U technology developers on the basis of their technical feasibility, readiness, markets and momentum. Research revealed that significant progress in CO₂U has been made in the past five years (2011-16). Momentum is favorable in four major markets—building materials, chemical intermediates, fuels and polymers. Within those markets, eight product categories merit priority based on the maturity of their technology, market promise, and potential impact on carbon emissions. Those categories are concrete, carbonate aggregates, methanol, formic acid, syngas, liquid fuels, methane and polymers. This roadmap presents a commercialization pathway for each of the eight categories.

The roadmap's recommendations include:

- Research to improve catalysis for CO₂ reduction must be funded.
- Research in improving electrolysis to produce hydrogen must be funded.
- Collaborations among research institutes, start-ups, governments and corporations for process integration of CO₂ conversion, hydrogen generation, and carbon capture must be funded.
- A CO₂ pipeline infrastructure is critical for the deployment of CO₂U technologies at scale.
- Governments have an important role in R&D funding, carbon pricing, support for certification and life cycle assessments, and more.

To the extent that climate benefits are a goal of those promoting CO₂U products, life cycle analysis (LCA) is essential. Considerable work is needed to standardize life cycle analysis methodologies for CO₂U.

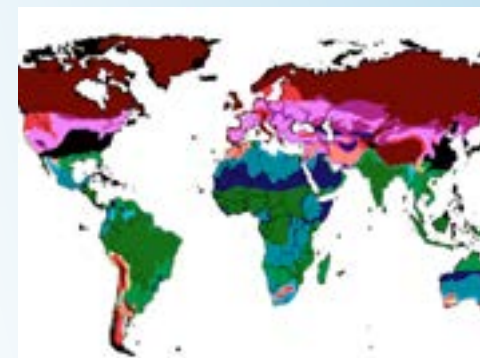
The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2016_roadmap1.pdf



ZEB/ZEH ROADMAP - TECHNOLOGY AND INSTITUTION –

March 2017

ZEB/ZEH Roadmap



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Energy consumption in the buildings sector accounted for 31% of final energy demand in the world in 2013 and is expected to reach 40% by 2050. To achieve the 2°C goal, significantly reducing CO₂ emissions from buildings is essential.

This roadmap explores technologies and systems for realizing zero energy buildings/zero energy houses (ZEB/ZEH). The roadmap includes a survey of studies by international organizations, national governments, local governments and industrial associations on this topic. These studies mainly covered building envelopes and installed equipment. Most of their discussions of air conditioning focused on temperature control. However in moderate and humid regions in Asia, where a huge increase in energy demand is expected, indoor comfort requires humidity control as well. Accordingly, this roadmap offers proposed strategies with both temperature and humidity as important factors. It covers many technologies, in four groups:

- Passive technology (structures) including heat insulation, heat reflection, light shielding, natural ventilation and airtightness.
- Active technology (equipment) including air conditioning, boilers, heat pumps, cogeneration dehumidifiers, solar water heaters, heat pumps, cogeneration, fluorescent lamps and LEDs.
- Energy management systems including communications equipment, passive equipment control, linkage with EV batteries, linkage with smart grids and energy storage.
- Renewable energy including solar power and wind power.

This roadmap offers proposed strategies for ZEB/ZEH in each climate zone. It finds that a wide range of energy-saving technologies have been applied to buildings, but the upfront cost of many of these technologies has been a barrier to adoption. The roadmap explores cost reduction and other strategies for promoting ZEB/ZEH. It finds that ZEB/ZEH requires the involvement of stakeholders, practical application of R&D results, and technology diffusion.

The ICEF Carbon Mineralization Roadmap can be found at
https://www.icef.go.jp/pdf/summary/roadmap/icef2016_roadmap2.pdf

DISTRIBUTED SOLAR AND STORAGE - ICEF ROADMAP 1.0

December 9, 2015



Distributed Solar and Storage



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Distributed solar and storage technologies could play a key role in reducing greenhouse gas emissions, strengthening grid resilience and improving energy access. A number of dynamics will shape the pace at which distributed solar and storage technologies are deployed and whether they can fulfil their potential. Key findings of this study include:

- Solar and storage technologies each offer considerable benefits when deployed individually. Combining solar and storage brings additional benefits, including a higher penetration of solar without variability challenges. The combination could also be transformative in emerging markets as a fast-track to electrification.
- Regulatory barriers that bias the market against solar and storage will need to be addressed if the market is to grow. These include connection charges, a lack of market structure for non-utilities to monetize generation, and taxes on distributed generation.
- The cost of storage is a more significant bottleneck than the cost of solar. For solar and storage to be a viable option, significant cost reductions in storage technologies are necessary.
- While energy storage can enhance the value of solar, there are other options for increasing the use of solar electricity and enhancing grid stability. These include renewables forecasting, demand response, flexible loads, thermal storage and power-to-gas. Cheap natural gas can provide low-cost, highly flexible generation that can complement solar, reducing the attractiveness of energy storage.
- To address possible future problems, we recommend sharing best-practice learnings widely, establishing standards and certification schemes, launching training programs for solar installers and engineers, reducing trade barriers and building consortia to facilitate collaboration on IT aspects of grid integration.

The ICEF Carbon Mineralization Roadmap can be found at https://www.icef.go.jp/pdf/summary/roadmap/icef2015_roadmap.pdf

The ICEF roadmaps provide important research on a wide range of technologies for helping achieve net zero emissions. They are an important resource for anyone working on these issues.

Hoesung Lee – Chair, Intergovernmental Panel on Climate Change

Energy transitions are neither easy nor quick. Understanding their many components requires rigorous analysis and realism. The ICEF roadmaps do just that: they provide essential information on different aspects of our energy systems and how they might change over time. I recommend them for anyone interested in this challenging topic.

Vaclav Smil – Distinguished Professor Emeritus, University of Manitoba

The ICEF roadmaps have provided important R&D pathways and a global vision for key decarbonization technologies needed for our sustainable energy future. They are an excellent resource for researchers and practitioners who cross disciplinary boundaries to develop transformative solutions for climate change.

Ah-Hyung (Alissa) Park

Chair, Department of Earth and Environmental Engineering, Columbia University

To reach net-zero in time will require deep decarbonization across all sectors that emit greenhouse gases into the atmosphere. For the truly hard to avoid emissions, carbon dioxide will be a critical tool. The ICEF roadmaps help to identify the key challenges, including R&D gaps, which will need to be overcome for demonstration, cost transparency, and adequate policy, to enable commercial deployment globally.

Jennifer Wilcox – Principal Deputy Assistant Secretary,

Office of Fossil Energy & Carbon Management, US Department of Energy

In recent years the ICEF Roadmaps have covered topics vital to fighting climate change, including CO₂ utilization, direct air capture and carbon mineralization.

I urge anyone working on these topics to study these roadmaps, which have been foundational for our work.

Larry Linden – Founder, Linden Trust for Conservation

Time is running out to develop new and much needed pathways for the hardest to decarbonize sectors, along with carbon dioxide removal. These areas have been critically overlooked and the ICEF roadmaps provide an ideal entry point for new actors looking to engage productively and strategically.

Remi Bouteille – CEO, Quadrature Climate Foundation