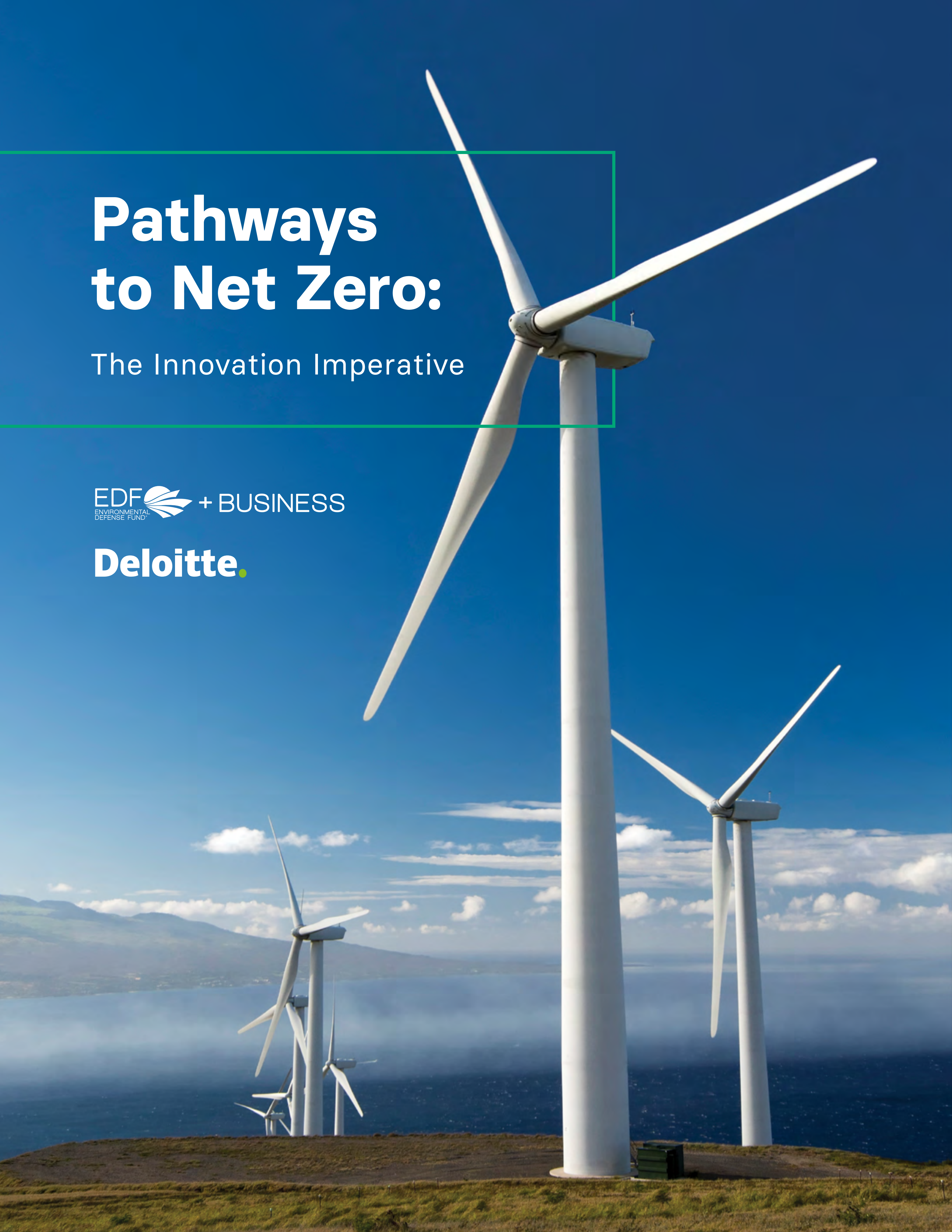

Pathways to Net Zero:

The Innovation Imperative

EDF ENVIRONMENTAL DEFENSE FUND + BUSINESS

Deloitte.

Table of Contents

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Executive summary

Climate technology is one of three main categories of climate abatement solutions that can reduce or remove greenhouse gases (GHGs) from the atmosphere to help avoid the worst impacts of climate change, in addition to **natural climate solutions** and **behavior change** solutions. Action across all three categories is critical to reach net zero emissions by 2050.

Due to a variety of long-standing systemic and economic barriers, current rates of development and deployment of climate abatement solutions are insufficient to reach net zero, leaving a **"net zero gap."** Bridging this gap by 2050 will require **innovation** across business, finance, policy and civil society to accelerate the deployment and development of new and existing climate solutions for the shared purpose of addressing climate change. This endeavor is not easy and will require overcoming long-standing systemic barriers to innovation.

Climate technology innovation is the process of helping climate technologies progress through various stages of **technological feasibility** and **commercial viability**, from small prototypes to scaled diffusion in the market. This report focuses on the collective **action** and **advocacy** opportunities available to **companies** and **investors** interested in catalyzing technological breakthroughs as part of the global effort to reach net zero.

Emissions flow through a series of **interconnected systems**, each containing a set of climate technologies that can reduce or remove greenhouse gas (GHG) emissions within and across sectors. Many climate technologies rely on consistent access to clean energy to reach their full abatement potential. As a result, near-term actions to accelerate **"The Big 3" — renewable electricity, grid connectivity & storage, and sustainable fuels** — will be critical to creating a foundational source of clean energy and maximizing the abatement impact of climate technologies across systems.

The private sector can engage in creative solutions to accelerate "The Big 3." For example, investors can back the development of batteries made from more sustainable materials; utility providers can leverage carbon footprint analytics to recommend an optimal renewables grid mix; and even companies from seemingly "unrelated" sectors can source renewable energy through power purchase agreements (PPAs) and enter coalitions advocating for clean energy policy.

To fast-track impact, these actions must happen in parallel with investments in **"The Extended 10"**— a set of 10 technologies that build on "The Big 3" to drive climate abatement throughout end use systems. "The Extended 10" technologies were chosen for their anticipated climate impact and collective involvement of all emitting sectors, including heavy industry, buildings, transportation, food & agriculture, electricity generation and also carbon removal.

Solving climate change represents one of the largest market opportunities in history, and companies and investors who move quickly to adopt and advance climate technology are likely to become leaders in a low-carbon future. These same companies must be intentional about managing **externalities** of climate technology whose deployment will influence equitable and environmental outcomes across socioeconomic, racial and geographic groups.

Figure 1. *Innovation Imperative Executive Summary*

Emissions Reduction Levers

Climate Technology

Behavior Change

Natural Climate Solutions

Climate technology innovation is the process of improving the **technological feasibility** and **commercial viability** of technologies, from prototype stage to scaled market diffusion. The rate of innovation today is insufficient to reach net zero by 2050, leaving a **Net Zero Gap.**

Companies across sectors should act now to accelerate technological breakthroughs and bridge the net zero gap. Companies and investors ahead of their peers in developing and deploying new climate technologies are likely to derive significant **business value** and establish a leadership position in a low carbon future.

Act

by championing and accelerating climate technology innovation

Advocate

for policies accelerating adoption of technologies

Figure 1. *Innovation Imperative Executive Summary*

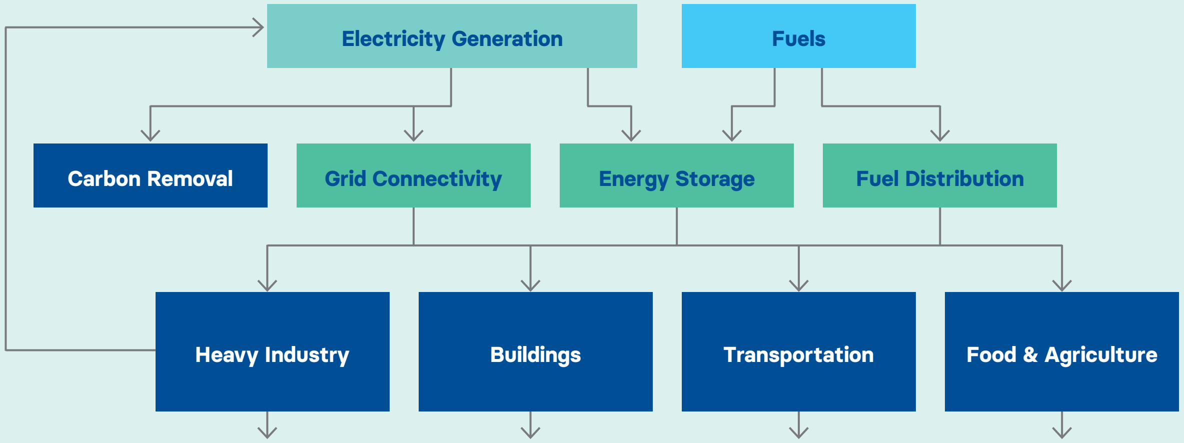
Prioritized Innovations

Emissions flow through of a series of interconnected systems. **“The Big 3”** energy technologies that enable climate solutions across systems should be prioritized to maximize the **availability of clean energy.**

Renewable Electricity

Grid Connectivity & Storage

Sustainable Fuels



Extended 10 Technologies

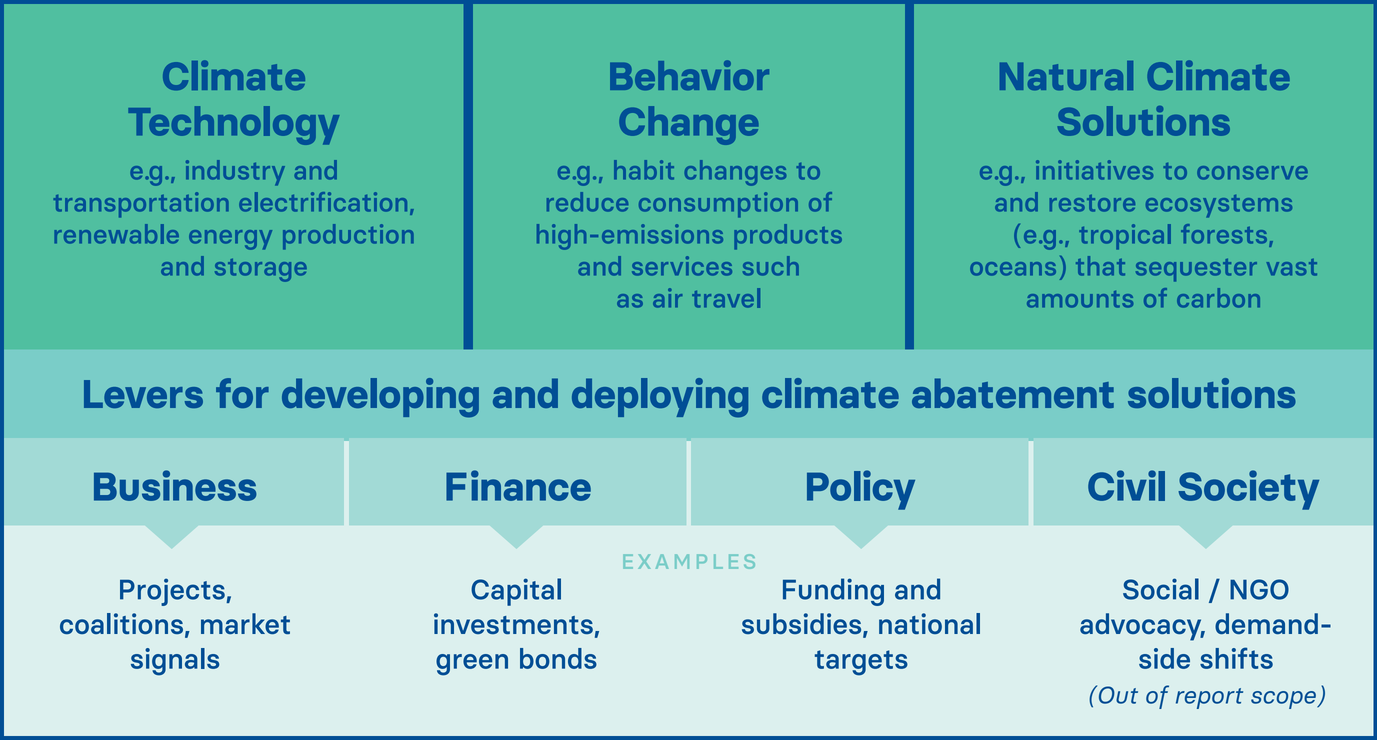
Scaling “The Big 3” must happen in tandem with initiatives to accelerate the “Extended 10” technologies with highest-abatement potential across sectors.

- Concrete CCUS
- Green Steel
- Alternative Refrigerants
- Building Insulation
- Battery EVs/ Charging Networks
- Alternative Proteins
- Livestock Methane Inhibitors
- Precision Agriculture
- Direct Air Capture
- Nuclear Fission & Fusion

Companies manage externalities by deploying climate technologies in a way that drives **equitable outcomes** across socioeconomic, racial and geographic groups.

Figure 2. *Three types of climate abatement solutions can reduce and remove greenhouse gases from the atmosphere to avoid the worst impacts of climate change*

Climate Abatement Solutions



Climate Technology
e.g., industry and transportation electrification, renewable energy production and storage

Behavior Change
e.g., habit changes to reduce consumption of high-emissions products and services such as air travel

Natural Climate Solutions
e.g., initiatives to conserve and restore ecosystems (e.g., tropical forests, oceans) that sequester vast amounts of carbon

Levers for developing and deploying climate abatement solutions

EXAMPLES

Business	Finance	Policy	Civil Society
Projects, coalitions, market signals	Capital investments, green bonds	Funding and subsidies, national targets	Social / NGO advocacy, demand-side shifts *(Out of report scope)*

Introduction

The willingness of the **private sector** to act on climate has never been stronger. COP26 inspired new climate commitments from business leaders across the world. ESG (environmental, social and governance) topics have become mainstream in organizational agendas, and companies are beginning to prepare for potential mandatory reporting on climate in the U.S. and beyond. Despite this progress, the Intergovernmental Panel on Climate Change's (IPCC) latest report has once again delivered a sobering and unequivocal message: it's not enough. **Current rates of progress remain insufficient to realize the commitments made under the Paris Agreement.** Its latest estimates find that limiting global temperature increases to 1.5° Celsius (C) above pre-industrial levels would require GHG emissions to peak by 2025 at the latest, in addition to achieving global net-zero emissions by around mid-century. Current global projections are well off track. However, with new opportunities and incentives presented by the passage of the Inflation Reduction Act in the U.S., the private sector has an increasingly significant opportunity to help avoid the worst impacts of climate change. **This report aims to arm business leaders and investors with the information and guidance they need to accelerate the development and deployment of one of many levers for climate action: climate technology.**

Climate technology — along with behavior change and natural climate solutions — represents one of three abatement solutions that can help reach net zero. Each category is essential and relies on strategic, mutually reinforcing actions across business, finance, policy and civil society. Climate technology refers to a set of machinery or equipment developed through the application of scientific knowledge and used for the practical purposes of reducing or removing GHGs. While business leaders can help drive impact across all three categories, this report focuses on climate technology. Technology offers a wide range of mechanisms to accelerate climate solutions, and company actions to support these mechanisms will vary based on their novelty to the market. Many climate technologies are not yet considered competitive in the market and require **innovation** to advance their **technological feasibility** and **commercial viability**.

This report builds on the first two reports of the ***Pathways to Net Zero*** series. The first report, ***A Guide for Business,*** makes the case for the critical urgency of reaching global net zero and outlines sector-specific pathways for getting there. ***The Decisive Decade*** subsequently provides a clear framework to help companies activate these potential abatement solutions within their businesses and supply chains. It makes clear the necessity of business acting **now** to address climate change. As the third report, *The Innovation Imperative* focuses on what happens next after companies deploy existing abatement solutions and still come up short on reaching net zero. In this case, incremental technology advancements and the repurposing of existing technologies for decarbonization applications can help bridge the gap. *The Innovation Imperative* demystifies the landscape of climate technology and provides a clear set of recommendations for how business leaders and investors can lead in a low carbon future through strategic action and advocacy that accelerate the development and deployment of the most promising climate technologies.

The Net Zero Gap

The good news is that most of the climate technologies needed to reach net zero already exist today.[1] The bad news is that 75% of them are not yet commercially deployed at scale. Even more prominent technology success stories, such as solar panels and electric vehicle batteries, took around 30 years to boast any remarkable impact.[2] With less than 30 years to go to 2050, climate technology innovation must achieve a rapid pace that far exceeds today's rate of progress.

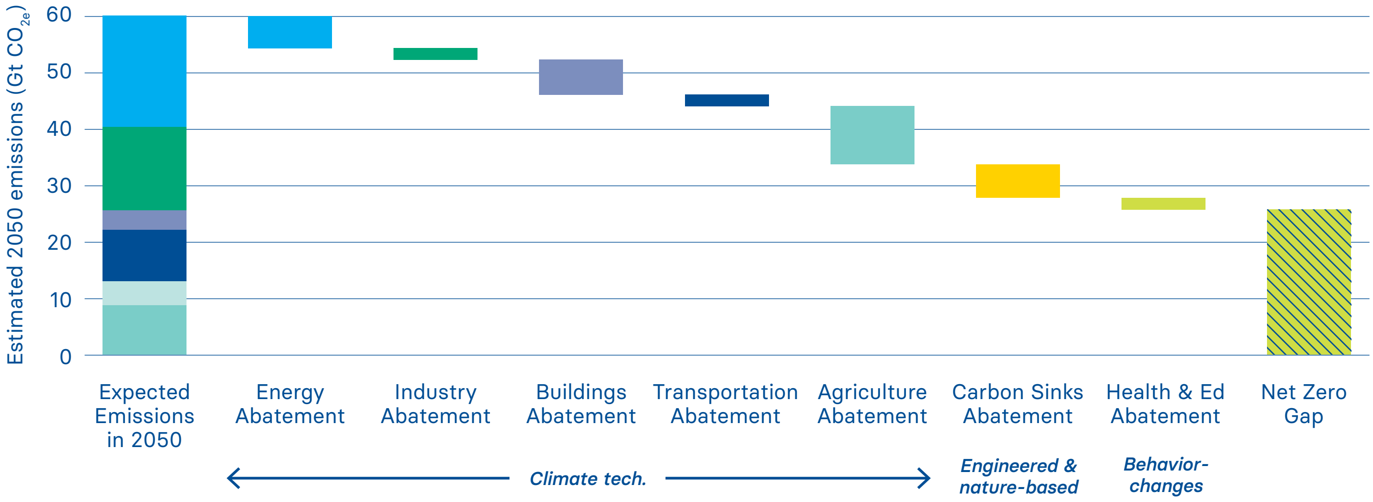
$38 trillion funding gap

The IPCC estimates $48 trillion in investment needed from 2020-2050 to reach net zero. We're currently on track to spend just $10 trillion, leaving a $38 trillion funding gap.

This challenge is illustrated by the **net zero gap.**[3] Figure 3 illustrates the extent to which existing climate solutions would abate emissions in 2050, assuming a business-as-usual scenario — where no further climate policies nor concerted technology innovation efforts take place in the next 30 years.[4] In this scenario, global 2050 emissions (represented by the left-hand bar) can be partially mitigated by deployment of **sectoral solutions** (energy generation, heavy industry, buildings, transportation and agriculture). Abatement is also expected from **carbon sinks** (e.g., "locking" carbon into naturally absorbing wetlands) and **behavior changes** (e.g., health and education to improve family planning and offset population growth). Even if these solutions are deployed between now and 2050, the size of the right-hand net zero gap (and associated investment gap[5]) demonstrates the shortcomings of global policy and current rates of innovation that amount to less than half of the reductions needed by 2050. The net zero gap exists in large part due to political inertia (including the influence of fossil fuel lobbying) and could shrink significantly through increased political appetite for action on climate. Indeed, in the U.S. it will shrink with the passage of the Inflation Reduction Act. However, the private sector cannot afford to wait before acting themselves. Business leaders should instead observe the climate crisis for what it is — both a threat to their future operations and a **compelling market opportunity** that can be seized through innovation positioning their companies as leaders in a low carbon future.

To shrink the net zero gap, public and private organizations will need to overcome persistent, systemic barriers that have historically limited much needed investment in climate technology innovation. **Insufficient infrastructure** to support climate technologies, such as limited electric vehicle charging networks, as well as **uncertain climate policies** that create moving targets for business decision makers on topics such as vehicle fuel standards, can make companies' climate investment decisions seem even more risky and nebulous. **Lack of public and private funding** for research and development (R&D), or **key input shortages**, such as insufficient renewable energy to produce green hydrogen through electrolysis, also significantly slow technology development.

Figure 3. *The net zero gap represents remaining emissions in 2050 in a scenario void of new climate policies and technological breakthroughs. Note: this analysis was conducted prior to the passage of the Inflation Reduction Act and does not consider investments or incentives included in the bill.*



2050 Sectoral emissions abatement enabled by today's solutions business-as-usual scenario

On the demand side, **lack of technological awareness** among potential buyers, evolving national and company targets, and dominance of legacy markets collectively lead to a **lack of demand signaling** for new technologies. Insufficient demand signaling results in part from information asymmetries. Increased attention to ESG reporting indicates progress towards **data transparency**; however, companies still experience a cumbersome process of measuring, verifying and sharing supply chain emissions data. Finally, **organizational and political culture** can hamper the willpower to innovate. **Short-termism** among business and government leaders, driven by incentive structures that reward quarterly returns and frequent election cycles, limit the investments that need to be made now to prepare for net zero in 30 years. Competitive inter-firm dynamics can also hinder the **trust, collaboration and knowledge sharing** needed to solve a problem of such scale.

Figure 4. *Existing market and incentive structures have restricted the effectiveness of actions needed to close the net zero gap*

Key challenges impacting the development and deployment of climate technology innovations

- Insufficient infrastructure
- Uncertain climate policy
- Key input shortages
- Insufficient funding
- Low awareness of existing techs
- Limited demand-signaling
- Limited data transparency
- Organizational/ political culture
- Short-term focus
- Lack of trust/ collaboration

Innovation Case Study

COVID-19 Vaccine Development

There is precedent for coordinated public-private action to overcome an urgent global crisis — most recently demonstrated by the development of the COVID-19 vaccine. Inspiring parallels can be drawn between this cooperative response and achieving net zero, but the success story points to important areas for future caution.

Situation

The pandemic had halted economic activity in a matter of months as case-related deaths rippled across the world, necessitating urgent collaboration between governments, companies and scientists on an unprecedented scale to produce a life-saving vaccine.

Innovation Levers

Rapid response was made possible by the sharing of scientific research, public-private partnerships that created strong demand signals, creative use of existing mRNA technology, and the competitive incentive for pharmaceutical companies racing to develop the first safe and viable product.

Innovation Failures

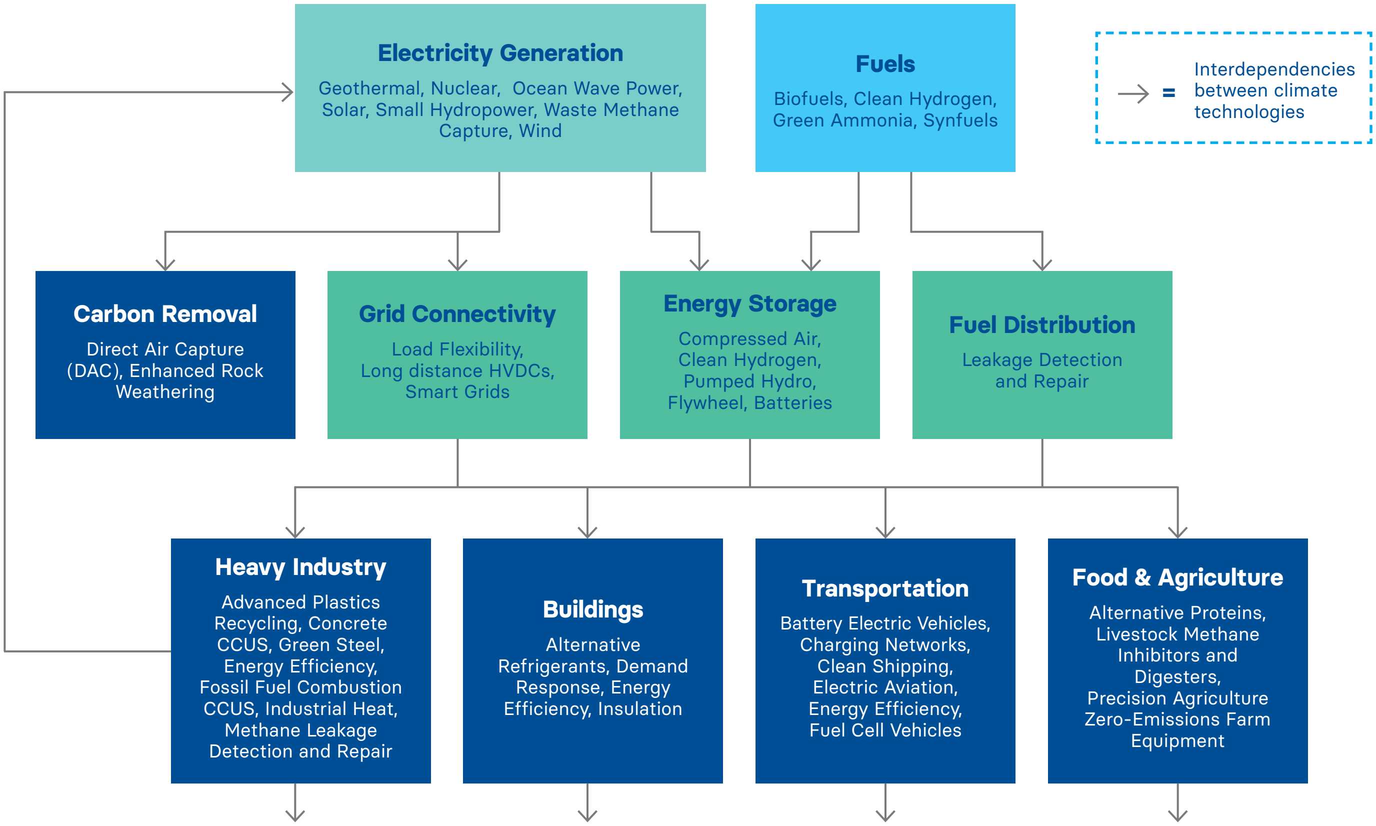
About 85% of global doses administered in the first seven months of the vaccine's launch were in high and middle-income countries, highlighting equity concerns that are just as relevant to the deployment of climate technologies. In addition, the politicization and profusion of misinformation regarding what should have been recognized as a universal public health issue delayed the solution, losing an unnecessary number of lives in the process.

The COVID-19 vaccine development offers both a useful model for successful collective action and a cautionary tale of how a technology's impact can be hindered by a range of socio-economic factors and inequities.

A Systems Approach to Climate Innovation

Closing the net zero gap will not be easy, and a haphazard pursuit of technologies based on their "new and shiny" appeal is a recipe for failure. Innovation encompasses **more than "disruptive" technologies**. Whether through revolutionizing process efficiency, shifting use patterns, or simply applying existing solutions to new customer segments or geographies, innovation is most effective when it seeks different approaches to problem-solving by first observing the flaws of a holistic system. Investments should be strategic and rooted in **systems change**, which begins with the understanding of how emissions flow from energy generation to end-use sectors of the economy. Each sector is responsible for producing a portion of global emissions, and each contains a set of climate technologies that can reduce these emissions.[6,7] The effectiveness of each technology is inherently **interdependent** — the progress of one may either stimulate or stifle the progress of another. Hydrogen-based fuel cells and electrification are both viable options for decarbonizing heavy-duty vehicles, for example, but prohibitively large infrastructure costs prevent the market from investing in their parallel application. As a result, it's likely that just one will emerge as the mainstream option for replacing internal combustion engines.

Figure 5. *Each system contains a set of climate technologies that can reduce or remove GHG emissions within and across sectors*



The crux of these systems lies in the dependence of end-use sectors on clean energy production, storage and distribution. Each sector's emissions abatement is directly influenced by how clean (low emission) its energy inputs are, and whether clean energy is readily available to use. This core dependency points to the systems responsible for energy generation as critical intervention points capable of disproportionate emissions reductions. It follows that systems change begins with innovation to position **renewable electricity** as the primary source of energy generation in 2050, which cannot happen without the support of **grid connectivity and energy storage.**

Sustainable fuels will be critical to complementing the future renewable energy mix as not all energy processes can be electrified due to technical and structural limitations. Taken together, these solutions can unlock the clean energy infrastructure needed to create the foundation for a net zero future.

“The Big 3”: Climate Technology Foundations

We refer to these clean energy foundations — and the prioritized technologies within them — as “The Big 3.” The first is **renewable electricity**, which focuses on **solar** and **wind** as the most readily available and cost-effective renewables for global scaling. The second is **grid connectivity and storage,** which includes **battery technologies, other low-carbon energy storage technologies** and innovations to **grid transmission** and **load flexibility**. Modernized grid infrastructure is essential for connecting renewable energy to its users and is a key factor in balancing the supply and demand issues currently hampering the intermittent nature of wind and solar renewables. A healthy supply of renewable energy can help produce not only clean electricity but **sustainable fuels,** which includes **biofuels**, **synfuels** and **clean ammonia** as the most promising clean energy sources for transportation methods that cannot be easily electrified (e.g., aviation and maritime shipping).

The remainder of this report provides an overview of prioritized technologies along with an actionable framework of recommendations for how companies and investors can **act** and **advocate** to accelerate innovation. **Companies** can influence the development of “The Big 3” and other climate technologies by incorporating these technologies into their own businesses, investing in partnerships and infrastructure, and advocating for the policies needed to catalyze their deployment. **Investors** can play a key role in encouraging their existing and prospective portfolio companies to take these actions while also engaging in direct investment and advocacy work.

Figure 6. *“The Big 3” technology sets*

The Big Three*

RENEWABLE ELECTRICITY

GRID CONNECTIVITY & STORAGE

SUSTAINABLE FUELS

*** See Appendix for additional sources and calculation methodology for each technology discussed below.**

Figure 7. *Innovation requires different types of engagement from the private*

Act by championing and accelerating climate technology innovation	By setting and meeting internal targets, signaling demand for new technologies, and collaborating with industry groups and suppliers to bridge research and funding gaps needed to scale solutions. Where relevant, acting can include customer engagement to spark interest in climate technologies.
Advocate for policies accelerating adoption of technologies	And align your trade association’s climate policy advocacy with those same goals. An active role in climate technology advocacy can include lobbying for concrete government action, dedicated investments in supporting infrastructure and global standards that will incentivize innovation.

Renewable Electricity Generation

All sectors of the economy rely on energy (from electricity to fuel to heat) to power assets and processes. Even energy-intensive processes in heavy industry that cannot be directly electrified will ultimately need massive amounts of renewable energy to decarbonize. Demand for an abundance of clean energy is best matched with the renewable sources most capable of widespread global reach: **solar** and **wind** energy. Thanks to impressive investments and advancements in the past few decades, solar and wind technologies can efficiently capture these renewable energy sources and transform them into readily deployable electricity. Both technologies are considered **technologically mature**, with continuous improvements to electricity conversion efficiencies credited for incremental breakthroughs (e.g., improved materials).

Figure 8. *The Big 3: Renewable Electricity Generation*

Renewable Electricity Generation

Key Climate Technologies: Solar, Wind

288 Gt
Potential CO_2e emissions abated between 2020-2050

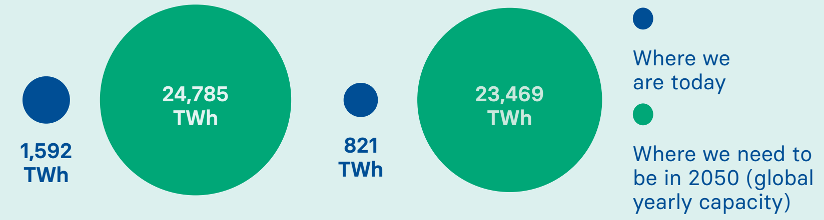
$280 B
Market size in 2050 (net zero scenario)

$9.5 T
Investment needed by 2050

$\$31/\mathrm{tCO_2e}$
Solar MAC*

$\$11\text{-}40/\mathrm{tCO_2e}$
Wind MAC

Wind Generation: **Solar Generation:**



Technology Feasability:**

1	2	3	4	**5**

Commercial Viability:

1	2	3	**4**	5

** Technological Feasibility and Commercial Viability is scored throughout this report using a framework adapted from NASA's and **IEA's Technology Readiness Level (TRL) scales**.

*MAC" as used throughout technology deep dives refers to the "marginal abatement cost" of technology

Despite the prominence of wind and solar as well-known and cost-effective climate technologies, they still experience commercial challenges throughout their lifecycles. The **installation** and **permitting process** for projects can be lengthy due to inefficient legal frameworks and community siting preferences, and *where* the renewables get installed will become an increasingly contentious topic as the net zero requirement for an abundance of wind and solar confronts limited land availability. A significant challenge for wind and solar is their **variable nature** dependent on the weather. Solar and wind power need to be complemented with a reliable mix of other renewables including geothermal (powered by the earth's heat) and hydropower (powered by water's flow), as well as with **utility-scale storage** infrastructure, to ensure a baseload of clean power is constantly supplied to the grid.

Wind and solar infrastructure also do not last forever, and retired wind blades are currently clogging landfills as they are difficult to recycle.[8] Even solar panels, composed of 95% recyclable materials, are not yet recycled at scale. Utilities can address waste and materials challenges by forming consortiums, **as GE and Engie SA are doing**, to research improved, more easily recyclable infrastructure designs.

Table 1.

Actions to innovate renewable electricity

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Utilities	→ **Set aggressive targets** (renewable energy production, infrastructure recycling) → Replace old infrastructure with new designs that support higher energy conversion rates → Customer engagement through education campaigns and tools	→ Consortium to fund and research new, more easily recyclable material and designs → **Partnerships with recycling companies and waste managers** to increase capabilities to repurpose unrecyclable items such as wind turbines
	All	→ Signal demand through **Power Purchase Agreements** (PPAs), sector-organized RE procurement contracts, purchase of high-quality verifiable RECs, and active engagement with utilities regarding capacity needs → Disclose top three initiatives taken to increase renewable energy use	→ Set targets and develop **roadmaps to achieve 24/7 clean electricity** (i.e., invest, advocate, and innovate to ensure infrastructure powered by RE at all times vs. annual matching)
ADVOCATE		→ More aggressive state and federal targets (locally and in countries with subsidiaries / operations) → Increased public funding and public-private partnerships (PPPs) to **offset upfront costs** → Push back on regulations limiting renewable energy production → Ensure voluntary standards and protocols incentivize and reward corporate renewable energy procurement	→ **Recycling requirements** for solar panels and wind turbines (supported by funding mechanisms such as reclamation bonds)

OTHER ESG CONSIDERATIONS

Construction of **mining sites** for rare earth minerals disrupts the economies and health of **local indigenous communities**, and a lack of substantial human rights policies has led to **violations of workers' rights**. The use of chemicals in manufacturing can generate **hazardous and radioactive byproducts**. Natural **habitats loss and degradation of land use** can be mitigated by locating wind/solar in previously degraded locations (e.g., unusable mines or along transportation corridors).

Investments to ramp up renewable electricity capacity will benefit both the climate and companies' bottom lines—it is estimated that **switching to solar energy in the U.S. can reduce commercial property owners' electricity costs by an average of 75%.**[9] However, renewable energy projects often occur at a significant scale difficult for individual companies to tackle alone. Walmart helps its suppliers overcome this challenge by creating the organizing infrastructure for group purchasing of renewable electricity through **Power Purchase Agreements (PPAs) with Schneider Electric**. The private sector can extend assistance to communities lacking purchasing power by advocating for government collaboration, like with the **U.S. Department of Energy (DOE) and U.S. Department of Health and Human Services (HHS),** to connect low-income households with wind and solar project developers.

Grid Connectivity and Storage

Today's grid is not prepared to support a renewables-dominant energy mix, making grid **infrastructure** technologies critical for connecting renewables to the populated areas and industry centers that need them the most. This can be achieved through the modernization of existing technologies, such as **high-voltage direct current** (HVDC) transmission lines that can reduce power losses over long distances and increase grid resilience in the event of natural disasters. **Smart grids** that leverage artificial intelligence and analytics will be key to managing energy supply and demand, as well as **utility-scale batteries** (currently predominantly lithium-ion) capable of storing hundreds of megawatt-hours to temper daily grid load fluctuations. Because batteries can be deployed where additional capacity is needed, they will play a large role in providing cheaper and more reliable renewable energy to isolated communities that might have otherwise relied on coal or gas. A more nascent application is the production of **clean hydrogen** as a storage vessel that can be readily converted back to electricity as needed.

Figure 9. *The Big 3: Grid Connectivity and Storage*

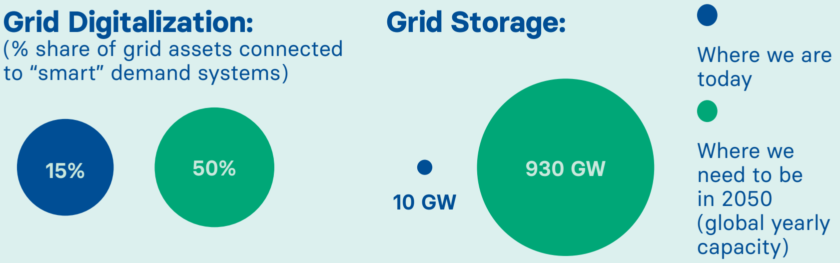
Grid Connectivity and Storage

Key Climate Technologies: Batteries, Clean Hydrogen (storage), Load Flexibility, Long Distance HVDCs, Smart Grids

Abatement estimate is excluded to avoid double counting with technologies that rely on the grid

$227 B
Market size for grid battery storage projects 2020-2050

$636 B
Annual grid spending needed in 2050


Grid Digitalization:
(% share of grid assets connected to "smart" demand systems)

Grid Storage:

Technology Feasability:

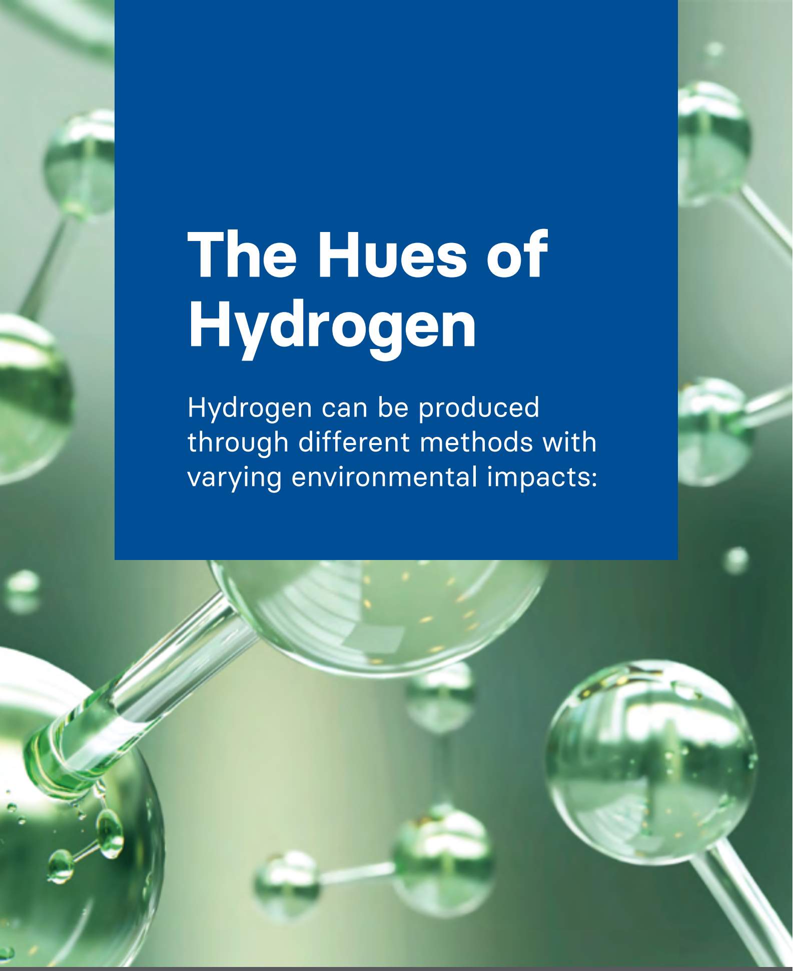
1	2	3	4	**5**	Grid infrastructure & technology
1	2	**3**	4	5	Clean hydrogen (storage)
1	2	3	**4**	5	Utility-scale batteries

Commercial Viability:

1	2	3	**4**	5	Grid infrastructure & technology
1	**2**	3	4	5	Clean hydrogen (storage)
1	2	3	**4**	5	Utility-scale batteries

While smart grids and supporting transmission technologies are proven to work at scale, **cost barriers** persist due to the overall lagging of the utilities industry. Customers have felt limited in their ability to advocate for innovations, such as **demand-response** programs, due to the inertia of longstanding billing and metering systems. Batteries also face commercial barriers—the dominant lithium-ion battery type is manufactured from rare materials subject to shortages, without sufficient circular economy infrastructure to enable their recycling at scale. **Battery storage** installations are expensive upfront and difficult to valuate in the long-term, in addition to facing regulatory hurdles.

Hydrogen storage must overcome a variety of technical hurdles to deliver on its promise. Storage in underground caverns is often recognized as the best way to store large quantities of hydrogen. However, cavern availability is subject to **geological constraints** and the risks of hydrogen leaking or



The Hues of Hydrogen

Hydrogen can be produced through different methods with varying environmental impacts:

Gray hydrogen is derived from natural gas made with fossil fuels. Most of the hydrogen produced today is gray hydrogen.

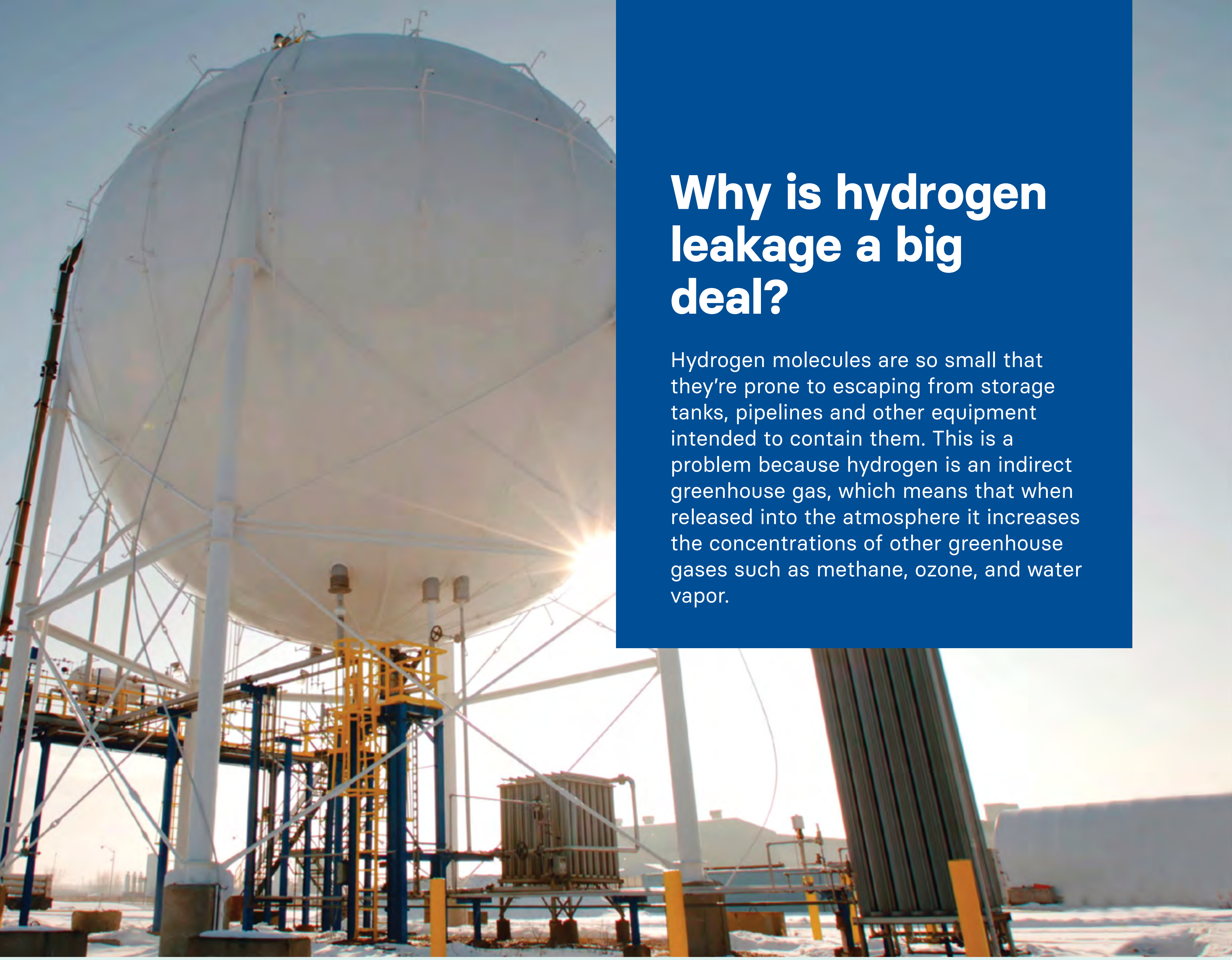
Blue hydrogen is derived from the same chemical processing technique that makes gray hydrogen, except the CO_2 generated in processing is captured and stored elsewhere.

Green hydrogen is produced by splitting water into hydrogen and oxygen through electrolysis using renewable electricity.

diffusing to mix with bacterial impurities in caves have yet to be fully understood.[10] Smaller-scale storage of hydrogen **in cryogenic tanks** is also being considered, but their deployment readiness is stalled by the issues of cost, hydrogen leakage and the relatively low energy density of hydrogen per volume.

As newer transmission and distribution players progress R&D to mitigate technological storage challenges, utilities must innovate the existing grid system to prepare for a future state of integration with renewable resources. They can begin by adopting more dynamic and optimized demand-response tools that leverage IT platforms to spread energy demand to off-peak periods on a daily and seasonal basis. **Demand-response** programs can be negotiated through bilateral contracts with both commercial and industrial customers. While entailing upfront effort and compensation packages to the participants, demand response programs are proven to ultimately avoid costs associated with overrunning energy capacity. Behavior shifts are often the true catalysts to the success of grid management technologies, and utilities can make grid dynamics more visible to customers through awareness campaigns on demand-response initiatives. **ConEdison**, for example, offers a package exchanging rebates on smart thermostats and electricity bills for the occasional allowance to briefly adjust electricity settings in times of high demand. When equipped with knowledge and incentives, every customer can play a contributing role.

Actors outside of the utilities industry have more sway over grid innovation than they might think, especially those planning electric vehicle (EV) fleets. For example: The **Johan Crujiff Arena in Amsterdam** is pioneering vehicle-to-grid technologies to supplement its solar and battery storage system during high-load events, providing rewards to the EV drivers attending the event. Companies can also engage in PPPs to build national battery supply chains, such as **GM's and Tesla's cross-sector coalition** advocating for U.S. tax incentives to battery manufacturing and processing.



Why is hydrogen leakage a big deal?

Hydrogen molecules are so small that they're prone to escaping from storage tanks, pipelines and other equipment intended to contain them. This is a problem because hydrogen is an indirect greenhouse gas, which means that when released into the atmosphere it increases the concentrations of other greenhouse gases such as methane, ozone, and water vapor.

"CLEAN" WITH CAVEATS

- Clean hydrogen's climate impact will depend on leakage rates—of both hydrogen itself and, in the case of blue hydrogen, of methane—into the atmosphere and the extent of its deployment
- Research from EDF estimates that, in the event of high hydrogen and methane leakage rates, swapping fossil fuels for blue hydrogen could contribute more to global warming in the following two decades
- On the other hand, deployment of green hydrogen with minimal leakage would nearly eliminate the warming impacts of the fossil fuels it replaces
- Effective leakage detection and repair technologies must not only be developed and implemented at scale, but also mandated and enforced through regulations

Table 2.

Actions to innovate Grid Connectivity and Storage

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Utilities	→ Increase number and categories of **demand-response** programs (across commercial and residential customers); increase adoption through education and customer outreach → R&D in **hydrogen leakage detection and repair**	→ R&D in new **battery** technologies (e.g., solid state) and increased recycling capabilities → R&D in high efficiency electrolysis or high efficiency **power-to-hydrogen-to-power** conversion technologies
	All	→ Work with utilities to maximize the use of **demand response** across facilities and demand the same from **suppliers** → Leverage **EV fleets as energy storage** and source ("vehicle-to-grid" technology)	→ Implement storage capacity targets (in addition to procurement targets) → Renegotiate contracts with utilities to demand **grid efficiencies** powered by new technologies → Consider **grid connectivity risks** in investments decisions
ADVOCATE		→ Funding and incentives to support **grid modernization** (e.g., smart-grids, HDVCs or utility-scale batteries) → PPPs to build national **battery supply chains**	→ Incentives (e.g., tax credits, R&D, innovation inducement prizes) for innovation in energy **storage** → **Regulatory** (environmental, safety) standards for hydrogen storage

OTHER ESG CONSIDERATIONS

Opportunity to maximize use of **micro-grid technologies** and new business models (e.g., pay-as-you-go) to secure energy for regions and communities with historically limited access to electricity. **Grid modernization costs** will likely be passed on to customers in the absence of proper regulation, risking disproportionate impacts to **end-users with lower incomes.**

Sustainable Fuels

Clean ammonia (made from clean hydrogen), certain **biofuels**, and **synfuels** are promising sources of clean energy for transportation methods that cannot be easily electrified (e.g., aviation and shipping).[11] Sustainable fuels overall have **yet to reach full commercial viability** — their current prices cannot compete with the subsidies that continue to pour into carbon-emitting fuels, and weak demand signals have resulted in a slow pace of investments into additional supply capacity.[12] Less technologically mature synfuels and biofuels need the support of recurring, guaranteed purchase commitments to justify upfront investments towards improving energy conversion rates that will ultimately make these technologies more affordable. This is especially important for the long-term success of biofuels that are made from waste or other feedstocks that don't compete with food uses (e.g., algae and organic waste) as opposed to those derived from crops or edible feedstocks (e.g., corn, soy, edible beef tallow, etc.). Biofuels derived from the latter create risks to food systems and could contribute to deforestation or GHG emissions from land use conversion. Without overcoming these barriers, biofuels may not produce their desired climate benefits.

Figure 12. *The Big 3: Sustainable Fuels*

Sustainable Fuels

Key Climate Technology Innovations:
Bio/Synfuels, Clean Ammonia

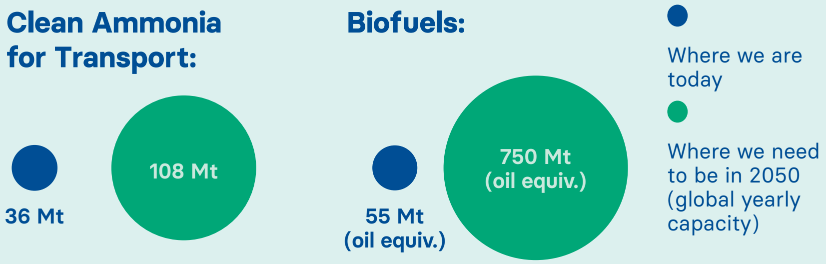
40 Gt
CO_2e abatement by biofuels, synfuels and clean ammonia (2020-2050)

27%
2050 biofuels share in transportation

230B gal.
Estimated commercial jet fuel 2050 market size

$33/tCO$_2$e
Biofuel MAC

$168/tCO$_2$e
Synfuel MAC



Technology Feasability:

1	2	**3**	4	5

Clean Ammonia

1	2	3	**4**	5

Bio/syn Fuels

Commercial Viability:

1	**2**	3	4	5

Clean Ammonia

1	2	**3**	4	5

Bio/syn Fuels

Clean ammonia also faces extensive challenges. Ammonia is a highly toxic and corrosive chemical that requires careful management. Further, its key ingredient, clean hydrogen, comes with the same environmental risks as discussed in hydrogen storage applications. If ammonia's risks to human and ecosystem health can be managed, and if hydrogen leakage can be mitigated, the use of clean ammonia in internal combustion engines or fuel cells will be extremely helpful for decarbonizing the shipping sector. For the maritime sector to decarbonize by 2050, at least 5% of vessels will have to run on zero-carbon fuels by the end of this decade. That is likely to be achieved by the use of clean ammonia (the first ammonia two-stroke engine will be on the market in less than two years). Significant work must be done to enable the transition, such as building new infrastructure, ammonia bunkering point or adopting a robust policy framework addressing the challenges related to ammonia. The **maritime sector** can make headway in their decarbonization goals by sending demand signals across the value chain to stimulate investment in clean ammonia and other sustainable shipping fuels like clean methanol.

Table 3.

Actions to innovate Sustainable Fuels

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Transport Fuel	→ **Clean ammonia** bunkering (shipping) feasibility studies and pilots	→ Implement port and airport refueling infrastructure for high-integrity **bio/synfuels**
	Food & Ag	→ Signal demand by setting and meeting clean **ammonia targets** (to replace traditional fertilizers), and through sector-organized procurement contracts	
	All	→ Signal long-term demand for high-integrity **bio/synfuels, clean ammonia** through targets, recurring collective purchasing agreements and commitments	→ Retrofit/reform supply chain infrastructure to support **fuel alternatives** → Set internal carbon-fees on **fuel**
ADVOCATE		→ National taxonomy and standards for **fuel alternatives**, e.g., by fuel source (to protect land use), by end use (e.g., X% of airline fuel to use SAF) → Phase-out of **fossil fuel** subsidies	→ **Hydrogen hubs** where industries with large energy needs strategically locate near clean energy sites → Cap-and-trade programs incentivizing high-integrity **bio/synfuels, clean ammonia**

The Aspen Institute is encouraging coalitions that organize cargo owners and suppliers to prepare such supply chains, and encouraging companies to set targets around the use of zero-emissions fuel in their value chain maritime shipping activities.

Companies of all sectors can strengthen **demand signals** for sustainable fuels, and many have a direct stake as employee air travel most likely factors into their own decarbonization goals. RMI and EDF are spearheading the **Sustainable Aviation Buyers Alliance (SABA)** to drive investments into high-integrity sustainable aviation fuel (SAF) and catalyze member engagement in policy-making efforts (e.g., Deloitte, Microsoft). Businesses can instill more confidence in their decarbonization agendas if they advocate for formalized standards ensuring the emissions integrity of fuel switching.

The role of hydrogen hubs as sites localizing all aspects of the production process (thus minimizing chances of leakage during transport) could be integral to clean hydrogen's success, and they are gaining more government attention. The **Advanced Clean Energy Storage (ACES)** project recently won a $504.4M loan from the U.S. Department of Energy. The project plans to convert excess renewable power to hydrogen and use it to balance the grid in Utah and Los Angeles. So long as the ACES project does not divert clean electricity from primary electrification uses, it can serve as a good experiment for hydrogen's potential as a feasible and clean power source while allowing for the evaluation of leakage risks during hydrogen's transport and underground storage.

OTHER ESG CONSIDERATIONS

In the case of ethanol (made from corn), various factors including the use of fertilizers in the agricultural process, and deforestation on behalf of corn have been shown to **eliminate known climate benefits**. In addition, **indirect land use change** threatens to worsen food supply scarcities already plaguing developing countries. Even if technically feasible, open questions remain regarding how big a role competitive biofuels **should** play in the future energy system.

“The Extended 10”:

Key Supporting Climate Technologies

By deploying the “The Big 3” to build a clean energy foundation, the private sector can help maximize the abatement potentials of other climate technologies. This approach alone, however, will not be sufficient to reach net zero. The timeline is too tight to allow for a sequential approach where companies can fixate on the “Big 3” before moving their attentions to other technologies. Instead, the “Big 3” must advance in parallel with coordinated initiatives to scale individual technologies across all systems. With too many options and too little time to bring every technology to scale, companies should take a targeted approach by analyzing the abatement potentials of technologies. Figure 14 illustrates **standalone**, best-case scenario projections of the cumulative abatement impact of each selected technology between 2020 and 2050 (“If we took every step to advance deployment of wind energy, assuming dominance over all competing technologies, how many Gt CO_2e would it abate?”).[13,14] The relative sizes of the bubbles provide directional guidance on each technology’s potential for impact—although, in reality, each technology’s abatement will depend on the deployment rates of other climate technologies, as well as investments supporting adoption.

Figure 13. *In addition to accelerating “The Big 3,” deploying a portfolio of “extension technologies” can drive climate abatement across end-use systems*

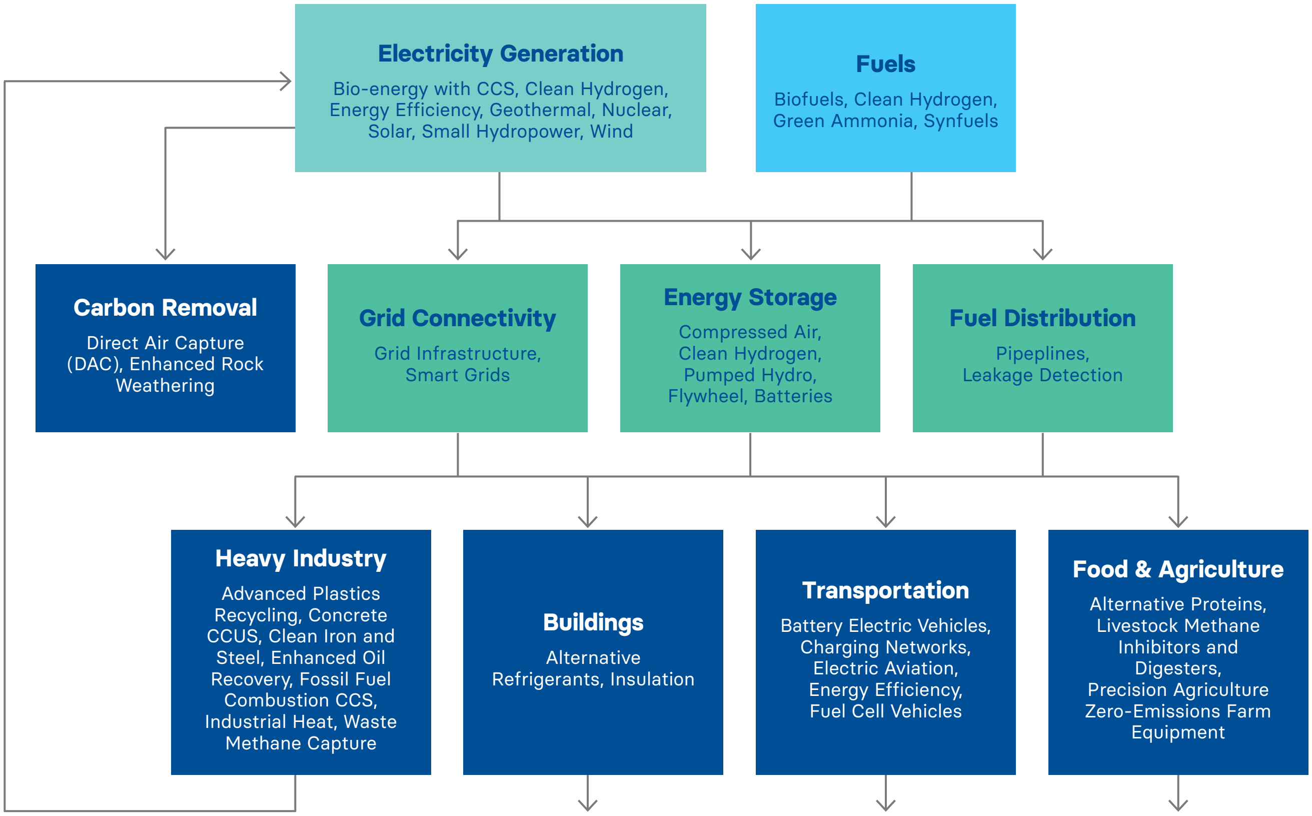
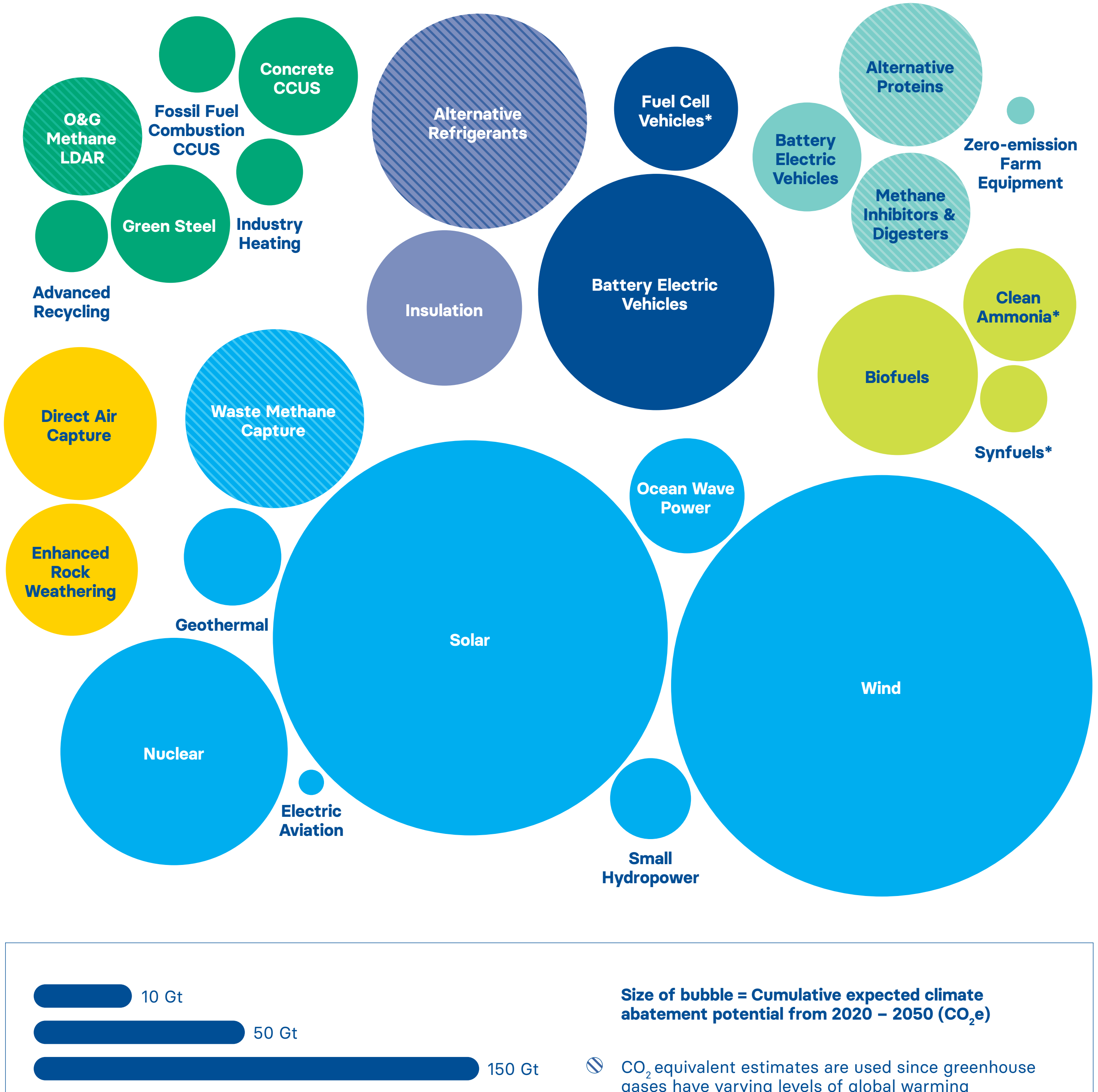


Fig. 14 *Understanding which climate technologies offer the largest opportunity for abatement is key to prioritizing actions and investments*



Size of bubble = Cumulative expected climate abatement potential from 2020 – 2050 (CO_2e)

- ● Heavy Industry
- ● Buildings
- ● Transportation
- ● Food & Agriculture
- ● Carbon Removal
- ● Electricity Generation
- ● Sustainable Fuels

▨ CO_2 equivalent estimates are used since greenhouse gases have varying levels of global warming potentials (GWPs). Methane and hydrofluorocarbons (used in refrigerants) linger in the atmosphere for a shorter duration compared to CO_2, but trap much more heat per molecule, making their abatement particularly urgent in the near-term.

GWP100 used for methane: 27x CO_2 ; GWP20 included in Appendix

GWP100 used for refrigerants: 771x CO_2; GWP 20 included in Appendix

* Climate technology for which clean hydrogen is a direct input. Clean hydrogen not included as a standalone technology to avoid duplication.

Table 4.

Assessing Technology Feasibility and Commercial Viability

Assessing levels of technology feasibility and commercial viability of climate technologies can inform recommendations for progressing innovation

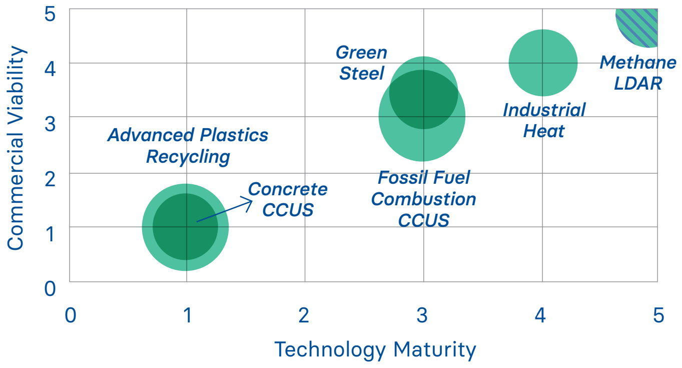
Technology Innovation Lifecyle	Technology Feasibility	Commercial Viability
1 Prototype	Technology prototyped in a lab and proven in test conditions	Very low probability of success; not deployed
2 Demonstration	Working prototype in expected conditions	Low probability of success; not deployed
3 Commercialization	Single full-scale functioning commercial unit is introduced	Ad-hoc deployment; unit attracts limited number of customers and financiers; not yet financially competitive
4 Early Adoption	Technology is commercially available and reliable but needs improvements to stay competitive	Limited deployment; cost (e.g., green premium) and performance gap remain; further integration with tech ecosystem required
5 Maturity	Stable; technology has achieved predictable growth; Incremental learning-by-doing continues	Deployed at scale in the relevant market; at par (in terms of price and performance) with carbon-emitting alternatives

Climate technologies can also be evaluated against dimensions of **technological feasibility and commercial viability**. Figure 15 maps the technologies by sector across these dimensions using the technology innovation lifecycle defined in Table 4.[15,16] Some technologies have reached peak maturity, like methane leakage detection and repair measures in the oil and gas industry. Others, like enhanced rock weathering, have barely made it past the theoretical stage to exist at the prototype stage. Understanding where a climate technology exists within the innovation lifecycle can inform which actions are most relevant to accelerating its development and deployment.

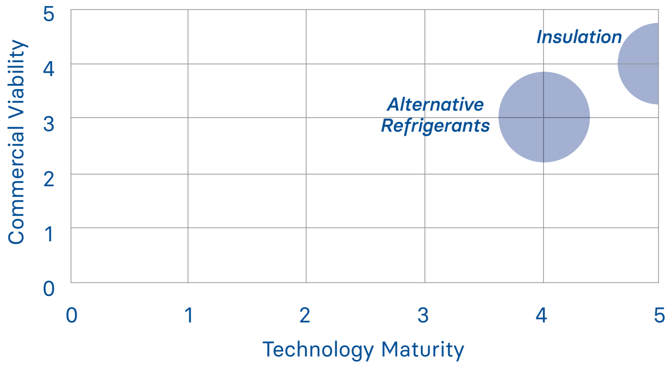
Keeping in mind the objective of maximizing abatement impact, technologies with the **highest abatement potential** should be prioritized for investment. In addition, since *all sectors* of the economy are responsible for a material share of global GHG emissions and will need to decarbonize, technologies with the **highest absolute abatement potential *per sector*** were prioritized to ensure each industry can apply at least one solution for its specific emissions scenario. This set of criteria, along with qualitative considerations given to externalities, resulted in the prioritization of "The Extended 10."

Fig. 15 *Some technologies are already mature, while others exist as prototypes*

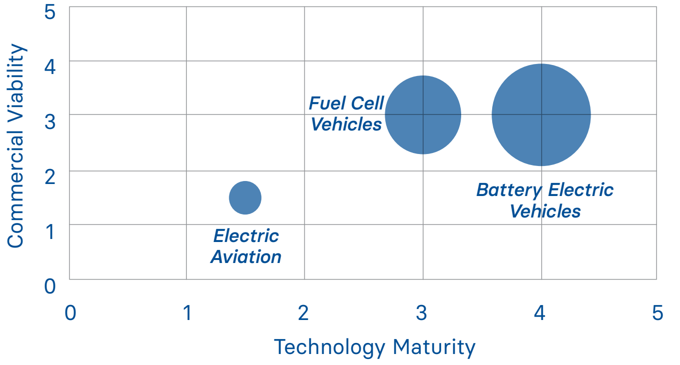
Heavy Industry



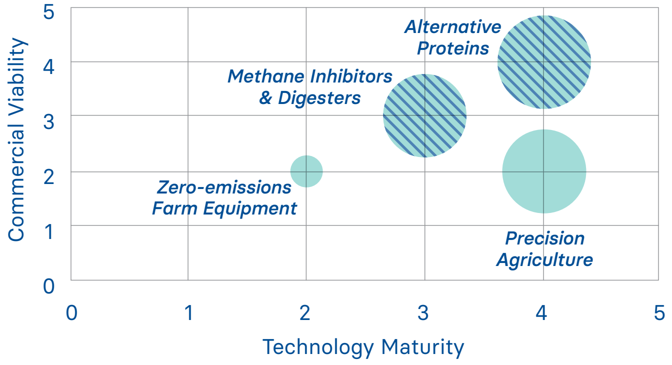
Building Technologies



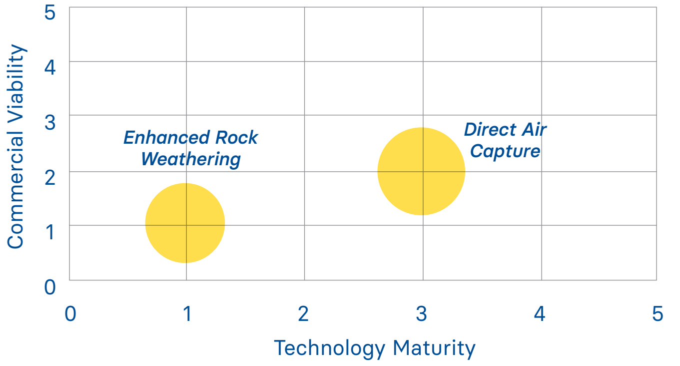
Transportation



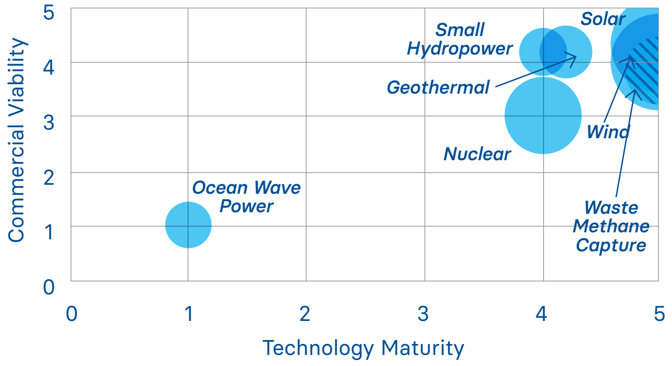
Food & Agriculture



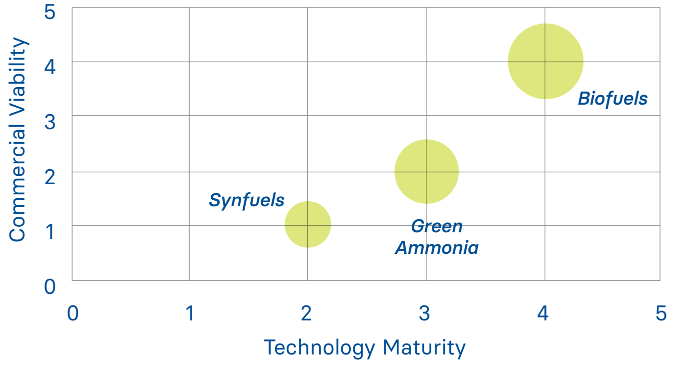
Carbon Removal



Electricity Generation



Sustainable Fuels



▨ GWP100 (global warming potential) used for methane: 27x CO_2; GWP20 included in appendix

GWP100 used for refrigerants: 2200x CO_2; GWP20 included in Appendix

Fig. 16 *"The Extended 10" were prioritized based on their expected climate impact and representation across sectors*

Heavy Industry	① **Green Steel**	"Green steel" refers to any low emissions steel production method. The lowest-emitting method is where direct reduction iron (DRI) is produced using "green" hydrogen (i.e., produced via electrolysis powered by renewables).
	② **Concrete CCUS**	Methods of capturing a portion of the CO_2 emitted during cement manufacturing and injecting it into fresh concrete during production as a form of storage.
Buildings	③ **Alternative Refrigerants**	Climate-friendly refrigerants with lower GWP, including "natural" alternatives (e.g., air, water, ammonia, carbon dioxide); also includes alternative methods such as natural refrigeration.
	④ **Insulation**	Materials and methods used to reduce heat gains or losses through buildings' envelope (roof, walls, windows, etc.). As a result, buildings consume significantly less energy for heating and cooling.
Transportation	⑤ **Transportation Battery EVs & Charging Network**	Any vehicle that uses a battery pack to store the electrical energy that powers the motor. Batteries are charged by plugging the vehicle into an electric power source.
Food & Agriculture	⑥ **Alternative Proteins**	Plant-based and lab-cultured technologies ("lab grown meat") offering protein-rich alternatives to meat products.
	⑦ **Livestock Methane Inhibitors & Digesters**	Methane inhibitors reduce the methane production of livestock by targeting digestion processes. Anaerobic digesters treat manure and produce energy in the form of renewable energy.
	⑧ **Precision Agriculture**	Technology (e.g., AI, drones, sensors) used to improve crop yields and assist with management decisions (e.g., with regards to fertilizer use, irrigation).
Carbon Removal	⑨ **Direct Air Capture**	CO_2 extracted directly from the atmosphere. The CO_2 can be permanently stored in geological formations, or be used (e.g., combined with hydrogen to produce synfuels).
Electricity	⑩ **Nuclear Fission & Fusion**	In addition to fission, includes fusion (combining atomic nuclei to release energy), and small modular reactors (prefabricated units produced at much lower costs, and shipped and sited on locations not suitable for larger plants).

Heavy Industry

Heavy industry contributes about **24% of global GHG emissions**.[17] Most emissions can be attributed to the chemical reactions and high-temperature environments required to fabricate some of the world's most ubiquitous products such as steel, concrete and chemical feedstocks (e.g., used in plastics, fertilizers). The sector is often described as "hard to abate" as production processes cannot be easily modified without altering the composition of inputs and/or outputs and high-temperature environments cannot be feasibly electrified with today's technology. However, known abatement technologies are being tested in the context of Heavy Industry processes. In addition to exploring the use of **biomaterials** and **clean hydrogen** as **alternative chemical feedstocks** to fossil fuel inputs, innovators are piloting various **carbon capture, utilization and storage (CCUS)** techniques to promote the circularity and sustainability of manufacturing processes.

Concrete Carbon Capture and Utilization & Storage (CCUS)

Concrete, the most widely used building material in the world, is produced by mixing **cement**, water and aggregates such as sand, gravel or crushed stones.[18] Most of concrete's emissions come from the manufacturing of cement, specifically from **calcination,** the chemical reaction that occurs when limestone and other materials are heated at very high temperatures in cement kilns. The **kiln firing process** powered by coal, oil or gas is responsible for most remaining cement emissions.

While the heating process can largely be electrified, limestone cannot be easily replaced, nor can the calcination process be adapted, without sacrificing the integrity of the cement and the safety of concrete structures. As a result, **concrete** does not have a plethora of known solutions for abating its largest source of emissions, leaving **CCUS** technologies as the most promising techniques for reducing concrete emissions by 2050. CCUS technologies **capture** a portion of CO$_2$ emitted during the kiln firing of cement. The captured CO$_2$ can then be **utilized** and injected back into the concrete itself to improve its strength (thus also reducing inputs required) or transported for geological **storage**. Concrete CCUS methods to extract CO$_2$ include **chemical absorption** with amine-based solvents and **calcium looping** (in which a series of calcination reactions are performed on the kiln flue gas). The U.S. and Europe are also experimenting with an **oxy-fuel** capture technique capable of higher CO$_2$ capture rates at the expense of requiring re-engineering to cement plants. All of these methods are in **prototype or early demonstration stages,** with a handful of installations in operation today that have not yet achieved competitive costs nor full carbon capture efficiency. The first 100% capture plant is expected to launch in 2024.[19] It is important to note that even 100% capture rates would not unlock concrete CCUS' full abatement potential unless **clean electricity** is used to power the heating process.[20]

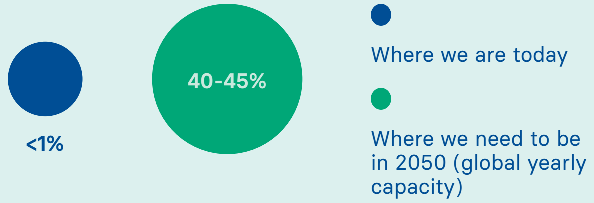
Figure 17. *The Extended 10: Concrete CCUS*

Concrete Carbon Capture and Utilization & Storage (CCUS)

3.7 Gt
Potential CO$_2$e emissions abated between 2020-2050

\$40-120/tCO$_2$e
Marginal abatement cost of CCUS technologies

Kilns Equipped with CCUS:



Technology Feasability:

1	2	3	4	5

Commercial Viability:

1	2	3	4	5

There are encouraging signs of appetite to fund **prototype and desmonstration pilot** projects of promising CCUS technologies that can eventually develop into full-scale demonstrations, as seen in consortiums such as **Project CLEANKER** (clean clinker).[21] This 26-member consortium of research organizations, providers and construction companies is using the **Buzzi Unicem Vernasca** plant in Italy to demonstrate the efficacy of calcium looping CCUS. Companies can create momentum in their own states by advocating for legislation to establish end and interim cement decarbonization targets, as California demonstrated with a **2021 Bill** directing its Air Resources Board to reduce the GHG intensity of cement by 2045.

Table 5.

Actions to innovate Concrete CCUS

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Construction & Real Estate	→ Fund prototypes of amine-based post combustion CC, and commercial scale pilots of oxy-fuel CC	→ Signal demand through low-carbon cement (through CCUS) procurement targets
	All	→ As part of new buildings construction, demand that concrete CCUS be used (and allocate budget accordingly); where not feasible, sponsor concrete CCUS pilot projects	
ADVOCATE		→ Signal demand through low-carbon cement (through CCUS) procurement targets for public buildings → Standards to ensure monitoring, reporting, and verification (MRV) of CO_2 sequestration projects → Construction of pipelines to connect captured CO_2 to sequestration sites	→ International carbon pricing mechanisms complemented by interim financial stimulus packages to compensate for asymmetric pricing pressures across regional markets

Despite the likelihood that CCUS will play a large net zero role for both concrete and regions currently entrenched in fossil fuel use, its rash deployment could complicate industrial decarbonization efforts if proper **guardrails** are not established. Project developers must ensure that the captured CO_2 that does not get injected back into concrete is adequately transported and **stored over meaningful periods** in **geological sites**. This process requires extensive technical expertise regarding the selection, monitoring and maintenance of storage sites in order to demonstrate secure storage for incentives and permits. Similar oversight of the monitoring, reporting and verification of “sequestered” volumes in utilized CO_2 in cement production is equally important, an issue that risks being overlooked in the absence of regulatory standards for projects.

OTHER ESG CONSIDERATIONS

CCUS projects have historically **overlooked local populations** in their efforts towards global decarbonization. While cement facilities piloting CCUS are likely to receive subsidies for their efforts, the nearby communities **directly affected by industrial pollution** receive no compensation nor have any say in how CCUS externalities are managed. Business partners should selectively invest in projects that **prioritize community engagement** and suggest proactive solutions to protect the neighborhoods in their areas of operation.

Green Steel

The steel sector is the largest industrial consumer of coal.[22] The sector's greatest shot at emissions abatement is green steel, which refers to **any low emissions steel production method**. Recommendations to decarbonize this sector must consider the various steel production methods and infrastructure used today.

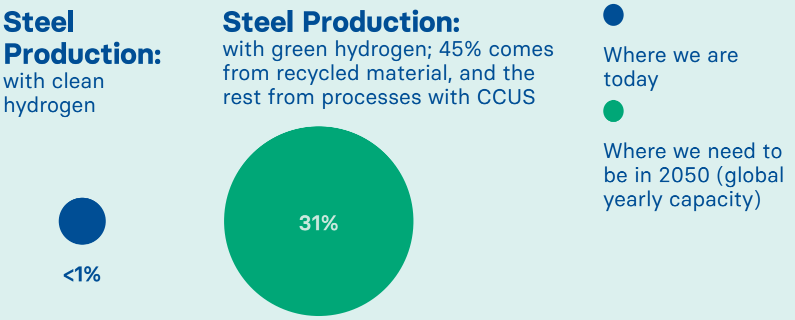
Blast furnaces (BF) are by far the most widely used steel production method today and use coal to convert iron ore into iron, then iron into steel. **Electric Arc Furnaces (EAF)** use electricity to melt (recycle) steel scrap into steel. The newest method **"direct reduced iron" (DRI)** reduces iron ore to iron through a chemical reaction which does not require combustion. Today, most DRI plants use a mixture of hydrogen and CO_2 but can be re-engineered to use green hydrogen so that water is emitted instead of CO_2.[23] Higher-emitting methods for producing green steel include using blue hydrogen (instead of green hydrogen) in DRI plants, as well as equipping DRI plants with CCUS capabilities.[24]

To decarbonize the steel sector, EAF plants should be consistently powered with **clean electricity**, and BF-BOF plants should be retired as soon as possible and replaced by DRI plants that can be powered by hydrogen or equipped with CCUS capabilities.

Figure 18. *The Extended 10: Green Steel*

Green Steel

12 Gt	**$150/tCO$_2$e**	**$278B**	**$2.5T**
CO_2 emissions abated by green steel (2020-2050)	Marginal abatement cost of CCUS technologies	Investment needed by 2050	Global revenue for the steel sector in 2019



Technology Feasability:

1	2	**3**	4	5

Commercial Viability:

1	2	**3**	4	5

Most of the barriers to scaling the more sustainable green hydrogen-powered DRI stem from the **availability of green hydrogen**. Most **DRI plant operators** have indicated their intent to use green hydrogen "once available" and where feasible but have started using blue hydrogen in the meantime. This constraint further emphasizes the need for widespread deployment of renewables to produce green hydrogen, and for careful approaches by both the private and public sectors in selecting the **smartest end-uses** for the limited green hydrogen supply (e.g., where no other path to decarbonization, such as electrification, is available).

Despite these barriers, steelmakers have recognized green hydrogen-powered DRI as the most viable route to realizing their emissions pledges, and green steel prototypes have already been championed in end-use sectors. **Volvo** announced "the world's first vehicle made of fossil-free steel from SSAB" (a steelmaker leading in low-carbon technologies) in 2021, and subsequently the **"first heavy-duty truck made from fossil-free steel"** in 2022.

Table 6.

Actions to innovate Green Steel

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Steel Supply Chain	→ Internal green steel targets → Recurring green steel and green hydrogen purchasing agreements (and collective agreements where incentives are aligned such as real estate/ construction)	→ Design all new steel manufacturing capacity to be hydrogen or carbon capture ready
	All	→ Signal long-term demand for green steel through targets (e.g., % of green steel used as input) and recurring collective purchasing agreements for green hydrogen (beyond internal needs)	→ Governance models to critically assess where green hydrogen is the best source of energy (to decrease pressure on limited inputs)
ADVOCATE		→ National targets, funding and roadmaps for renewable energy → Green steel procurement mandates for the public sector → International collaboration and funding to accelerate decommissioning of BF-BOF plants and re-engineering of DRI plants	→ International carbon pricing mechanisms complemented by interim financial stimulus packages to compensate for asymmetric pricing pressures across regional markets

While the use of green and blue hydrogen and CCUS will be key to decarbonizing steel production (responsible for 8% and 16% of 2020-2050 cumulative projected emissions reductions, respectively), 40% of 2020-2050 cumulative direct emissions reductions is expected to come from **material efficiency strategies** along the steel supply chain alone.[25] Most of this projection is attributed to actions from downstream sectors (e.g., extending building lifecycle while retrofitting with energy efficient lighting, heating, etc. or working with architects to evolve building design to reduce the need for steel and cement). Thus, while green steel technologies can address supply-side emissions, the end-use construction sector must take ownership and action of the demand side.

OTHER ESG CONSIDERATIONS

The global blast furnace fleet is ~13 years old (a fraction of their average lifespan), with 85% of fleet capacity located in **emerging economies**. International collaboration (e.g., funding, IP sharing) is needed to ensure these economies have the resources to accelerate the **retirement of BF-BOF plants** and the **retrofitting of DRI plants**. This will be key to reaching net zero and will benefit local populations through **reduced air pollution**.

Buildings

The heating and cooling of buildings accounts for **~10% of global greenhouse gas emissions**.[26] These emissions will continue to rise as urbanization progresses, air conditioning becomes more affordable to populations in developing countries, and as periods of extreme heat become longer and more frequent due to climate change. In addition to embracing renewable electrification (e.g., heat pumps), commercial buildings can target pressing and cost-effective abatement priorities by pursuing **alternative refrigerants** and improved **insulation**.

Alternative Refrigerants

Given the very high global warming potential (GWP) of hydrofluorocarbons (HFCs) used in current refrigerants (~771x more potent than CO_2 over a 100-year period), switching to **alternative refrigerants** is a global imperative to address emissions from the building sector.[27] **Synthetic** alternatives include hydrofluoroolefins (HFOs) (some of which have a GWP of less than 1). **Natural** alternatives made from ammonia, water (both with GWP of near zero), hydrocarbons (e.g., propane and isobutene with GWPs of less than 4) and carbon dioxide (GWP of 1) are already commercially available.[28]

The commitments of 197 nations to phase out HFCs made in the **2016 Kigali Amendment** to the Montreal protocol is a promising step towards a global refrigerant swap-out, but remaining technological and commercial challenges threaten to slow implementation. While some natural refrigerants, such as CO_2, are cheaper than higher-GWP alternatives, most have either raised **safety concerns** regarding toxicity and flammability, or do not yet operate at competitive efficiency levels.[29] In addition, many old AC systems are incompatible with alternative refrigerants and will require **costly retrofitting or replacement**. Any company that owns or leases real estate can take action by **setting public targets and committing funding** for the replacement of higher-emitting refrigerants with alternatives.

Figure 19. *The Extended 10: Alternative Refrigerants*

Alternative Refrigerants

40 Gt
Potential CO_2e emissions abated between 2020-2050

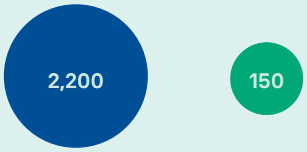
$284 B
Savings from energy efficiencies in U.S. alone, 2020-2050

Refrigerants: Average GWP of refrigerants used today

Refrigerants: Goal average GWP of refrigerants in 2050

● Where we are today

● Where we need to be in 2050



Technology Feasability:

1	2	3	**4**	5

Commercial Viability:

1	2	**3**	4	5

Table 7.

Actions to innovate Alternative Refrigerants

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Construction & Real Estate	→ Equip all new buildings with systems and appliances with the most efficient, lowest-GWP appliances (and retrofit old buildings); ensure the recovery and destruction of refrigerants at end-of-life	→ Reduce fundamental need for refrigeration by improving building insulation (refer to *Insulation* solution) and other methods (e.g., natural refrigeration)
	All	→ Set public targets to replace systems and appliances with the most efficient low-GWP appliances (for owned buildings, request similar actions from landlords in leased buildings) → Ensure the recovery and destruction of refrigerants at end-of-life	
ADVOCATE		→ Accelerated approval of residential and commercial use of alternative refrigerants → R&D funding for alternative refrigerants innovation	→ A globally agreed-upon roadmap to aggressively phase down HFCs (akin to a detailed, ambitious, follow-up to the 2016 Kigali Amendment)

OTHER ESG CONSIDERATIONS

Refrigeration and air conditioning systems using HFCs have proliferated over the past decades, leading to significant increases in the quality of life, particularly in developing countries. However, continued use of these emissions will effectively **"lock in" avoidable emissions**. It will be critical to rapidly bring down the cost of alternative refrigerants systems (e.g., through IP sharing, subsidies) to encourage the retirement of old units while allowing populations to **maintain their quality of life.**

Insulation

Improved insulation (e.g., through new materials and building design) is an adjacent technology that helps reduce refrigerant demand altogether. It represents the first step towards the overarching goal of retrofitting and constructing **net zero buildings.**[30] By tempering heat changes in a building's envelope (e.g., roof, walls, windows, etc.), insulation allows buildings to consume significantly less energy for heating and cooling, which reduces the need for high-GWP refrigerants, covered in the prior section).

Insulation technologies have been around for decades, but continued R&D has increased efficiency gains through innovations like **green roofs** that use soil and vegetation as living insulation, **cool roofs** that reflect up to 80% of solar energy, and **dynamic glass** that responds to light exposure to reduce energy load. The largest barrier to adopting these technologies is getting buy-in to their

Figure 19. *The Extended 10: Alternative Refrigerants*

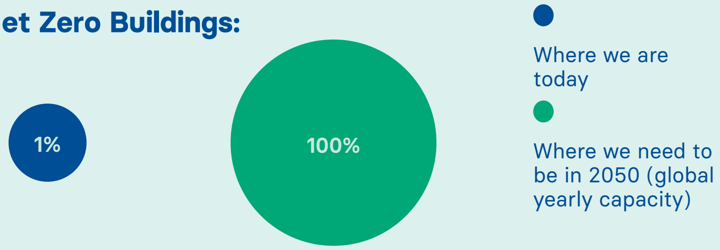
Building Insulation

21 Gt
Potential CO_2e emissions abated between 2020-2050

$40%
Potential reduction in energy use for commercial buildings from insulation and retrofits

15 months
Avg. time to ROI for installations in commercial buildings

Net Zero Buildings:



Technology Feasability:

1	2	3	4	**5**

Commercial Viability:

1	2	3	**4**	5

Table 8.

Actions to innovate Building Insulation

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Construction & Real Estate	→ Achieve LEED Zero certification across owned buildings using improved insulation retrofits → Launch education/awareness campaigns to highlight environmental and long-term financial benefits of insulation to end-users (to encourage up-front investments)	→ Work with architects and engineers to ensure the newest, most effective insulation practices and materials are continuously incorporated in new buildings
	All	→ Collaborate with landlords and other tenants to plan and co-fund large-scale insulation retrofits in leased buildings (e.g., large office leases) → Include energy efficiency standards requirements in new owned and leased buildings	
ADVOCATE		→ Mechanisms (e.g., direct funding, tax credits, clean bonds, etc.) to fund residential and commercial building retrofits → Education/awareness campaigns to highlight environmental and long-term financial benefits of insulation	→ National, municipal, and state building energy efficiency standards

cost cases. Sometimes, upfront costs of insulation material are higher than the less-efficient alternatives (despite ultimately accruing more lifetime savings), and proper installation of newer insulation techniques requires the employment of skilled architects and engineers.

Landlords, who can pass on most energy costs to tenants, will likely decline to bear the cost burden of large insulation retrofit projects without regulation. The same goes for real estate developers, who do not face strong incentives to maximize future energy efficiencies at the expense of lower profits. Innovation is required to address these **split incentives** and rethink the relationships between key actors. Each company can contribute **by directly engaging with landlords** of leased offices and developing new collaboration and funding mechanisms for building retrofits. At a macro level, coalitions advocating for net zero building mandates also play a role. **C40,** a climate advocacy group, is partnering with 19 U.S. mayors and the World Green Building Council to propose a plan ensuring all new U.S. buildings are net zero by 2030. Companies can achieve net zero buildings by jointly funding new insulation projects (like the EU private sector does for **EENSULATE**) and by pursuing **LEED Zero certification** through insulation retrofits.

OTHER ESG CONSIDERATIONS

Benefits of insulation go far beyond reductions in CO_2 emissions and lower utility bills. Insulation has been proven to enhance **well-being** by improving air quality, preventing the growth of mold and reducing noise pollution. Investments to retrofit affordable housing are expected to generate savings through energy efficiency and improved health outcomes, thereby promoting more **equitable living environments** for communities who already spend a greater portion of their income on energy costs.

Transportation

The transportation sector contributes to **~15% of global emissions**, which largely come from the automotive, aviation and maritime shipping sub-sectors' combustion of fossil fuels.[31] Using **today's battery technologies**, the latter two cannot be feasibly electrified for long-haul ventures, as electrification would require so many cumbersome battery packs that ships would slow significantly, and planes would not be able to take off. As a result, **Sustainable Aviation Fuels (SAFs)** made from biomass and combined with kerosene have emerged as one of the most sustainable options for powering planes in the short-to-medium term. **EDF's Sustainable Aviation Fuel Handbook** offers guidance and solutions for companies, policymakers, airlines and fuel producers for advancing high-integrity SAF. **Biofuels** or **synfuels** in the form of methanol can also power ships' internal combustion engines, as can **clean hydrogen** and **ammonia made from clean hydrogen** (which can both be used in tandem with electric motor fuel cells). While SAFs are farther along the innovation cycle, hydrogen-based fuels and certain biofuels are still being piloted and come with a range of considerations (e.g., safety risks of storing hydrogen, availability of refueling networks, etc.).

Battery Electric Vehicles (EVs) and Charging Networks

Electricity stored in batteries is the most viable option for decarbonizing the automotive sub-sector (with abatement impacts directly correlated to the grid's source of electricity). **Light-duty** passenger EVs supported by lithium-ion battery technology are already available across several automotive brands. Even if further innovation is needed to overcome reliability and range constraints, electrification **today** is technically feasible for 65% and 49% of **medium-duty and heavy-duty trucks**, respectively.[32]

Upfront acquisition costs remain a barrier across all categories of EVs. However, a range of publicly available **funding, incentives and grants** are available to corporate leaders, which helps strengthen the business case for fleet electrification. **EDF's Fleet Electrification Solution Center** provides a step-by-step guide to help organizations turn their electrification goals into reality.

Figure 21. *The Extended 10: Battery Electric Vehicles and Charging Networks*

Battery Electric Vehicles and Charging Networks

48 Gt
Potential CO$_2$e emissions abated between 2020-2050

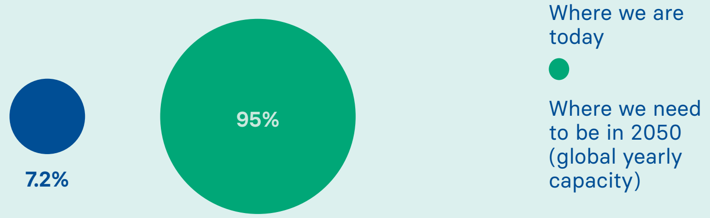
$7.5 B
Allocated by the US government to build a charging stations network

$823 B
Addressable market globally by 2030

$19/tCO$_2$e
Light-duty EV's MAC

$156/ tCO$_2$e
Medium-duty EV's MAC

Miles driven globally that are electric:



Technology Feasability:

1 2 3 [✓ 4] 5
Battery EVs

1 2 3 [✓ 4] 5
Charging Networks

Commercial Viability:

1 2 [✓ 3] 4 5
Battery EVs

1 2 3 [✓ 4] 5
Charging Networks

Potentially further adding to price pressures (and slower adoption), some automotive manufacturers have warned that a severe **battery shortage** could happen within the next three years.[33] This reinforces the importance of scaling recycling capabilities, and funding and accelerating innovation of batteries made from less rare and cheaper materials (companies innovating in this field are also trying to maximize other benefits, including faster-charging and using less polluting material).

Lastly, building and maintaining an **extensive, modernized** (e.g., high-speed) **charging network** will be key to accelerating adoption and unlocking the full abatement potential of EVs. Any company can play a role in this, as demonstrated by **Starbucks'** partnership with Volvo and ChargePoint to install EV chargers in its parking lots roughly every 100 miles along a 1,350 mile route from Denver to Seattle.

Table 9.

Actions to innovate Battery Electric Vehicles and Charging Networks

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Automotive Supply Chain	→ Cross-industry R&D investments and pilots of alternative battery materials and technologies (e.g., solid-state batteries) → Public charging stations subsidies (e.g., for low-income communities)	→ Cross-industry funding to increase recycling capabilities
	All	→ Set fleet electrification targets (for owned/ leased, light-, medium- and heavy-duty vehicles) → Develop fleet electrification strategy and implementation roadmap (leverage EDF's Fleet Electrification Solution Center)	→ Build charging stations (e.g., across office locations, stores, etc.) and offer at-home charging stations subsidies for employees
ADVOCATE		→ 100% state and federal battery EVs fleet; early retirement of carbon-emitting vehicles → Requirements that stations built with federal dollars be located within reasonable distance of each other, and consider low- income populations' needs	→ More stringent vehicles efficiency and emissions standards, paired with credits/subsidies for new vehicles for low-income populations

The electrification of road vehicles will not be complete without due attention to **public transportation**. The public sector is already considering plans to electrify e-buses, with some nations like **India** issuing millions of dollars in incentive packages. Companies can advocate for similar EV rebates for public transit in their markets, or take the additional step of outlining their own public sector plan to fund public electrification, like **ComEd** has done in conjunction with the state utilities regulator in Illinois.

Electrification of public transit is one of many transportation infrastructure improvements that can affect more sustainable behavior shifts in end-users, in addition to prioritizing the construction of walkable urban landscapes.

OTHER ESG CONSIDERATIONS

Prohibitive **upfront costs** of EVs and **inequitable dispersion of charging infrastructure** exacerbate existing inequities as low-income populations already disproportionally live in areas with higher air pollution. Mining and manufacturing of rare toxic materials used in batteries involve **polluting and unethical practices** (e.g., child labor) which must be addressed through a mix of policy, corporate action and increased recycling rates.

Agriculture

The food and agriculture sector faces the **dual challenge** of reducing its **22% share of global emissions** while increasing farm yields to feed a growing population.[34] This sector is unique in that most of its emissions come from GHGs **more potent** and/or **shorter-lived** than CO$_2$.[35] The most prevalent of these is methane (27x more potent than CO$_2$ over a 100-year time frame, and around 80x more potent over a 20-year time frame), produced mainly by livestock digestion processes and manure. The second most prevalent, nitrous oxide (273x more potent than CO$_2$ over a 100-year time frame), mostly comes from the use of nitrogen-based fertilizers.[36] Another main source of agriculture emissions is its conversion of nature's dwindling carbon sinks, such as wetlands and forests, into farmland.

Alternative Proteins

When accounting for emissions attributed to land use change, global livestock production accounts for approximately 16.7% of global GHG emissions.[37] **Alternative proteins** have made significant strides towards competitiveness with animal proteins in recent years and can help address the challenge of providing nutritious food to a growing global population. Many **plant-based** products are now widely accepted, albeit at a price premium. 66% of Americans report that they are willing to try **lab-grown proteins**. However, in contrast to plant-based products, lab-grown proteins are not yet legal in the U.S. (although oversight by the FDA and USDA appears imminent).[38] Furthermore, their status as a healthy and sustainable food source remains highly disputed, in part because today's life cycle assessments (LCAs) do not sufficiently assess these claims due to a lack of reliable data and the developmental stage of the technologies involved. As a result, lab-grown proteins will require continued investment and innovation to receive regulatory approval and gain full consumer acceptance.

Figure 22. *The Extended 10: Alternative Proteins*

Alternative Proteins

17.5 Gt
Potential CO$_2$e emissions abated between 2020-2050

$290 B
Estimated global market for alternative meats by 2035

Nearly 1 out of 4
Americans report eating less meat in the past year. Health and the environment are major reasons

Technology Feasability:

1	2	3	**4**	5

Commercial Viability:

1	2	**3**	4	5

Table 10.

Actions to innovate Alternative Proteins

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Food Manufacturers	Use LCAs and systems analyses to identify opportunities and priorities for improving environmental outcomes of alternative proteins (as compared to the foods they are intended to replace)	Develop accurate labeling and marketing to help consumers make informed choices about lab-grown proteins products
	Industry Agnostic	When using alternative proteins, favor alternatives that maximize environmental benefits while minimizing negative social and economic impacts	
ADVOCATE	Industry Agnostic	Standards and government oversight to ensure lab-grown proteins are safe for human consumption	Programs that maximize the net societal benefits of lab-grown proteins

OTHER ESG CONSIDERATIONS

Alternative proteins have the potential to disrupt complex food production systems that include billions of farmers, ranchers, fishers, food processors and others. The **risks of unanticipated ripple effects** and adverse socioeconomic impacts must be carefully considered. Investments in Alternative Proteins innovation should not happen at the expense of building resilient, sustainable animal-protein supply chains (refer to *Methane Inhibitors* and *Digesters* profile) as **both types of proteins will play a key role** in a sustainable and equitable food future.

Livestock Enteric Methane-reducing Solutions

Innovation is also required to decrease livestock lifecycle emissions, including for methane inhibiting technologies, genetics, health improvements and anaerobic digestors. **Methane inhibitor** technologies, such as enteric methane-reducing feed additives and drugs, can be introduced into livestock feeding regimens to reduce methane produced during their digestive processes (technically referred to as *enteric fermentation*). It is critical that feed additives, in addition to methane-reducing drugs, successfully enter the market for confined livestock systems, where beef and dairy cattle are centrally fed each day. To scale, methane inhibitors will require further evaluation and regulatory oversight to assure their use is safe for cattle and for the consumers of dairy and meat products, as well as financial programs to alleviate the initial financial burden for farmers and accelerate adoption.

Outside of changes in cattle's diet, larger farms can install **anaerobic digesters** to convert livestock manure into renewable fuel, which can then be converted and sold as electricity. Anaerobic digesters have been around for decades but remain prone to **methane leakage**, which can be addressed through advocacy for accountability through leakage detection and repairs standards, as well as through maintenance training programs. Since methane leakage reduces the environmental benefits digesters are meant to provide (i.e., absolute reduction of methane emitted), leakage rates should be factored into methane credit calculations (for both credits and the sale of renewable fuel outputs) so that the benefits are not over-estimated and incentives to reduce leakage remain.

Unfortunately, anaerobic digesters are **unaffordable for smaller farms** that do not produce enough methane to justify today's high upfront investment costs. Thus, it is critical that policies also address the needs of these smaller farms through financial incentives and schemes that qualify methane inhibitors for reduction credits on the voluntary carbon credit market.

Figure 23. *The Extended 10: Methane Inhibitors and Digesters*

Methane Inhibitors and Digesters

13 Gt	$400K-5M	25%-40%
Potential CO_2e emissions abated between 2020-2050	Range of the cost for an anaerobic digester in the U.S.	Reduction in enteric methane from using 3-NOP, a methane inhibitor

Technology Feasability:

1	2	**3**	4	5

Commercial Viability:

1	2	**3**	4	5

To address research gaps and make methane inhibitor technologies more appealing, companies can co-invest in R&D. Cargill and ZELP (Zero Emission Livestock Project) have combined methane oxidation and data processing technology to develop a cattle wearable that neutralizes methane as it is exhaled. Cargill's product will undergo further testing at an agricultural university to better understand this technology's effectiveness and barriers to adoption.

Table 11.

Actions to innovate Methane Inhibitors and Digesters

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Meat & Dairy Supply Chain	→ Improved regulatory process to safely and quickly approve new enteric methane reduction drugs or feed additives → Incentivization of renewable electric production instead of biomethane injection into pipelines which extends fossil natural gas usage → Build procurement and financial systems incentivizing the deployment of methane inhibitors in the supply chain → Trial existing solutions and monitor progress	→ Scale best available technologies, leveraging incentives and learnings from near-term pilots → Co-invest (with industry peers) in enteric emissions reduction R&D and pilots
ADVOCATE		→ Prioritized approval process of new methane inhibitors proven unharmful to animal and human health → Specific mandate for USDA (governmental agency) to make climate change mitigation a statutory priority, supported by R&D in agricultural methane solutions → International collaboration and funding to improve cattle diets in developing countries	→ Incentives to encourage the adoption of methane inhibitors (e.g., feed additives and animal drugs) and digesters on small farms (e.g., direct funding, conditional subsidies, etc.)

OTHER ESG CONSIDERATIONS

Changes in **cattle diets** can directly impact carbon intensity. In developed countries, where cows mostly already eat an efficient diet, increases in unsaturated fats or carbohydrates have been shown to decrease methane, while increasing feed efficiency. In developing countries, improvements to address nutritional deficiencies are needed to improve productivity and reduce carbon intensity. Methane captured by digesters from existing sources provides substantial global climate benefits. However, digesters do not address many of the local environmental impacts, particularly ammonia emissions. Treatment of digestate to reduce ammonia emissions will be needed to address local **air quality impairment**.

Precision Agriculture

Figure 24. *The Extended 10: Precision Agriculture*

Precision Agriculture

9.8 Gt	**$14.4 B**	**$40-$100 B**
Potential CO_2e emissions abated between 2020-2050	Projected 2027 global market size	Estimated cost savings to farmers by 2030

Technology Feasability:

1	2	3	**4**	5

Commercial Viability:

1	**2**	3	4	5

Precision agriculture refers to the use of **technologies and agriculture practices** aimed at increasing farming efficiency and effectiveness. It leverages **digitization and monitoring technologies** (e.g., AI, drones, sensors, weather stations, satellite imaging, tractor GPS, etc.) to inform farm management decisions. Precision agriculture also includes **variable rate technologies**, which allow fertilizer and water to be applied at different rates across the same field. This has the triple benefit of improving crop yields, reducing water consumption, and reducing overall fertilizer rates and associated nitrous oxide emissions by adjusting fertilizer source, application time, rate and method to crop needs. Other innovative technologies include **soil additives** that can enhance the soil's microbial makeup and crops' utilization of nitrogen, which also reduces fertilizer nitrogen inputs.

While many precision agriculture technologies may increase farmers' profits in the long term, their initial investments and associated risks can be untenable for farmers living on sometimes thin margins. In addition, while most digitization and monitoring technologies are technologically mature, most rely on robust and constant internet coverage. As long as internet coverage gaps (in developing countries and some U.S. regions) prevail, farmers may be reluctant to adopt new technologies. For instance, if weather modeling might not work in their area, it may not be an attractive investment for their enterprise.

Overcoming these adoption barriers for smallholders is possible with the intervention of multiple actors. Technology producers are developing smaller versions of precision agriculture devices that better suit the needs and spending power of small farmers, while NGOs and microfinance institutions are helping farmers gain access to credit. For example, EDF and the Farmers Business Network launched **an agricultural financing program** incentivizing farmers who implement regenerative agricultural practices. In the U.S., companies advocating for the digitization of agriculture should ensure the spending of the **2021 Bipartisan Infrastructure Bill,** which includes $65B to expand broadband connectivity and $47B to protect against cybersecurity threats, is properly allocated to rural agricultural areas.

Table 12.

Actions to innovate Precision Agriculture

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Farmers Tech. Providers	→ Partnerships to train and educate famers (e.g., on new techs, ways to retrofit old equipment) → Credit mechanisms adapted to farmers' needs (e.g., lease and buy, low-interest loans)	→ Increase hiring of technology talent into the agriculture industry to "demystify" technology and the use of data in decision making
ADVOCATE		→ Private-public partnerships (PPPs) and funding to build internet infrastructure across rural areas → Awareness campaigns, including signaling of leading products and practices	→ Private-public partnerships (PPPs) to replicate success of precision agriculture innovations across (global) regions and value-chains

OTHER ESG CONSIDERATIONS

From droughts to floods, developing countries have been disproportionately **impacted by climate events** over the past few years. At the same time, farmers in these countries are the **least resourced to adapt**, while respecting local, historic and indigenous practices. It is critical that advances in precision agriculture be shared with these populations through education campaigns, IP sharing, grants and direct funding of technologies.

Carbon Removal

Carbon removal will be a **last-mile enabler of net zero**, tasked with eliminating the emissions that are expected to persist in hard-to-abate sectors even after other climate technologies are applied. While nature-based carbon sinks (and their preservation) are critical to achieving this task, the IPCC considers the addition of engineered carbon removal as "unavoidable" given the current emissions trajectory.[39]

Direct Air Capture

Direct Air Capture (DAC)[40] is considered the most promising technological solution for removing already-emitted CO_2 and will become critical if global temperature limits are exceeded (in addition to **natural climate solutions,** which play an outsized role in storing/removing CO_2). DAC can use chemical solutions to remove CO_2 from the atmosphere ("liquid DAC"), or use solid filters to bind with the CO_2 molecules ("solid DAC"). Both methods allow for the **CO_2 to be permanently stored in geological formations** (the recommended end-use) or otherwise used for industrial and commercial processes (e.g., in food processing or combined with hydrogen to produce synfuels).[41] DAC will require **large amounts of renewable energy**, meaning it will compete with the plethora of climate technologies reliant on clean power (some of which present a stronger or more urgent case for emissions abatement, such as electrification of heavy industry processes). However, DAC projects located near renewable energy sources can take advantage of **excess renewable energy** (particularly where storing excess energy is not practical or feasible). Nineteen DAC plants are in operation worldwide as of 2021, but more **large-scale demonstrations** will be needed to refine the technology and reduce risks associated with geological storage (including CO_2 leakage during transport, seismic activity and water pollution).[42] Increased deployment of DAC will require government incentives, as DAC offsets prices are significantly higher than other offsets available on the voluntary market.[43]

To accelerate DAC and ensure long-term viability, companies can take the next step to set **carbon-negative targets**, like **Microsoft** pledged in 2020. Companies can also help lower the price of DAC by **funding early-stage DAC companies**. Earlier in 2022, a collective including **Stripe, Alphabet, Shopify and Meta** funded an advance market commitment to buy an initial $925M of permanent carbon removal between 2022 and 2030. Given the nascency of DAC, the public sector should develop **standards** to ensure its effectiveness and transparency through the **monitoring, reporting and verification** of CO_2 sequestration projects. Companies can advocate for incentives to fund large-scale DAC hubs like the four planned in the **Department of Energy's $3.5B Infrastructure Law**.

Figure 25. *The Extended 10: Direct Air Capture (DAC)*

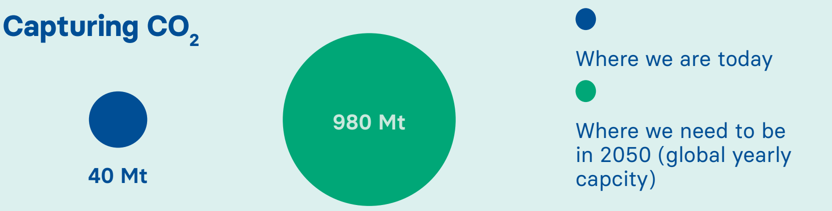
Direct Air Capture (DAC)

11 Gt
Potential CO_2e emissions abated between 2020-2050

$250-600
Cost of 1 t/CO^2 captured (vs. >$50/t$CO_2$ for afforestation offsets)

$129M
Allocated to DAC by the DOE in fiscal 2022 (up from >$10M 2009-2019)

Capturing CO_2



Technology Feasability:

1	2	**3**	4	5

Commercial Viability:

1	**2**	3	4	5

Table 13.

Actions to innovate Direct Air Capture (DAC)

	Near-term (2022-2025)	Medium-term (2025-2030)
ACT	→ Include DAC offsets in a portfolio approach to sourcing carbon offsets → Collective “advance market commitments“ to directly fund early-stage DAC companies, signal demand and decrease cost of DAC offsets	→ Set and implement roadmaps to meet carbon-negative targets
ADVOCATE	→ Incentives (e.g., grants, tax incentives, public procurement contracts, etc.) to fund large-scale DAC hubs to further improve technology and decrease marginal costs → Standards to ensure monitoring, reporting and verification (MRV) of CO_2 sequestration projects → Approval for large-scale DAC hubs contingent on studies assessing impact of the hubs on local communities	→ Accounting and reporting standards that recognize the value of CO_2 captured and stored (vs. captured and sold to industry) → R&D in carbon storage methods

OTHER ESG CONSIDERATIONS

There are concerns that DAC serves as **an excuse to extend the life of fossil fuels infrastructure**, weakens corporate climate targets and takes pressure off governments to push climate policy. In addition, one use of CO_2 captured through DAC is Enhanced Oil Bed Recovery (EOR), which leads to more fossil fuels being emitted. In addition to hindering climate action, prolonging the use of fossil fuels will perpetuate **health inequities** through increased air pollution in the low-income neighborhoods and communities of color that disproportionately live close to coal and power plants.

Until DAC is proven to effectively remove CO_2 at significant scale and viable costs, uncertainties will remain regarding its contribution to net zero. Renewables’ end-uses must be determined with caution, as DAC should not detract clean energy resources from more predictable, high impact solutions **nor should DAC be used as an excuse to delay near-term climate investments**.

Electricity Generation

As emphasized with "The Big 3," enabling access to clean energy at global scale is arguably the greatest unlock to decarbonizing our economy— around **23% of global emissions are attributed to electricity and heat**.[44] While hotly debated, **nuclear energy** already plays a key role in decarbonization, providing 50% of the U.S.' clean electricity supply in 2021.[45] While a variety of safety and public perception concerns must be addressed, nuclear is expected to be a key contributor to a decarbonized world.

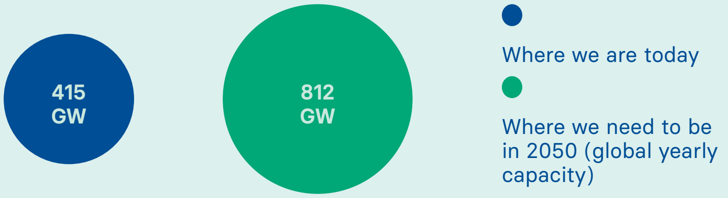
Figure 25. *The Extended 10: Nuclear Energy*

Nuclear Energy

45 Gt
Potential CO_2e emissions abated between 2020-50

658 GW
Capacity supplied by fleet in 2050 not existent today

$107/tCO_2e$
Advanced nuclear (e.g., SMRs and Gen IV reactors) MAC



Technology Feasability:

1 | 2 | 3 | 4 | **5**
Fission

1 | **2** | 3 | 4 | 5
Fusion

1 | 2 | **3** | 4 | 5
Small Modular Reactors

Commercial Viability:

1 | 2 | 3 | **4** | 5
Fission

1 | **2** | 3 | 4 | 5
Fusion

1 | 2 | **3** | 4 | 5
Small Modular Reactors

Nuclear Energy

Whether through **fission** (splitting atomic nuclei) or **fusion** (a less mature but safer method of combining atomic nuclei), nuclear is an uninterrupted, plentiful source of clean energy with a significantly smaller land footprint than any other clean energy source: The DOE estimates that it would take around 3 million solar panels, or 430 wind turbines, to produce the same amount of power as a typical commercial nuclear fission reactor.[46] However, concerns around numerous issues have limited nuclear deployment in many jurisdictions over the past few decades. These include **radiation** from nuclear accidents, inadequate capacity to safely dispose of **radioactive waste**, the technology's contribution to nuclear **weapons** proliferation, very high capital **costs** (frequently running over budget) and the **long time** required to complete facility construction. Even transitioning from conventional fission plants to future **fusion plants**, which proponents have claimed as feasible for decades, is fraught with obstacles. Fusion techniques rely on a steady supply of tritium fuel produced by fission plants that will eventually be shut down, making tritium one of the most expensive substances on the planet. A possible alternative approach is found in **small modular reactors (SMRs)**, which are prefabricated fission reactor units that may help reduce high construction costs while providing greater flexibility in co-locating with renewables sources thanks to their size.

For nuclear to secure its seat at the clean energy table, it must earn the public's favor. Utility companies can lead **education campaigns** with the help of nonprofits that convene public and private sector stakeholders to develop policies and communications accelerating nuclear. These campaigns will be more effective if SMRs are recognized as a safer and less-costly solution contributing to clean energy. Companies can help achieve this by engaging in public-private partnerships supporting SMR pilots, as seen in the **DOE's cost share award** approved for Carbon Free Power Project LLC that aims to provide up to $1.4B for the deployment of a 12-module power plant in Idaho.

Table 14.

Actions to innovate Nuclear Energy

		Near-term (2022-2025)	Medium-term (2025-2030)
ACT	Utilities	→ Communication and education campaigns highlighting: – The benefits of nuclear: low carbon footprint, role in balancing the grid when renewables are not available, significantly smaller land requirements compared to wind and solar – Reduced risks of new technologies **(fusion, SMRs)**	
	All	→ Engage utilities to identify optimal locations for **SMR** pilots based on expected energy needs (mostly from heavy industry) and utilities' planned energy mix	
ADVOCATE		→ PPPs to accelerate design approval and increased funding for **SMR** pilots	→ R&D funding to address tritium shortage issues → R&D to reduce waste volumes and radioactivity

OTHER ESG CONSIDERATIONS

Health and environmental risks are linked to the accidental release of radioactive nuclear waste (during transportation or disposal), although these risks impact health and environment on a smaller scale compared to fossil fuels. Overburdened communities bear the brunt of these facilities, given that the siting and permitting are typically in low-income areas.

Conclusion: Every Company has a Stake in the Net Zero Future

Any company or investor, regardless of sector, can participate in climate technology innovation. There are plenty of promising technologies and systems changes to **act** on, whether by adopting in-house projects, partnering with other purpose-oriented companies to advance R&D or adding targeted investments to portfolios. It is important for the private sector to **advocate** for the policies that enable a dynamic climate innovation environment through strong demand signals and aggressive funding.

Every effort will be needed to build a net zero future, starting with investments in **"The Big 3":** renewable electricity, grid connectivity and storage, and sustainable fuels. These investments must happen concurrently with the development, piloting and scaling of "**The Extended 10"** technologies to ensure the world is armed with the abatement solutions needed to fulfill its net zero promise before time runs out.

Companies ready to step outside of their organization and become leaders in global emissions abatement can champion a plethora of actionable initiatives recommended in this report. As they do so, it's imperative they manage innovation externalities with an equitable agenda. Marginalized populations have disproportionately shouldered the burden of anthropogenic climate change — breathing the polluted air from nearby factories, working dangerous supply chain positions and enduring the brunt of increasingly prevalent natural disasters. The future must be different. Companies at the forefront of innovation may succeed in their climate pledges but will fail in their commitments to social responsibility if the planet's most disadvantaged inhabitants continue to be left behind.

Global commitments may refer to 2050 as the deadline to limit global warming, but what we achieve in this Decisive Decade will indicate whether climate technologies and other solutions are on track to reach the finish line in time. The urgency of the climate crisis cannot be overstated at this point. Left untreated, it will cripple the global economy but addressed promptly and effectively, it can continue to usher in a wave of new business opportunities, particularly for first movers in the transition to a low-carbon world.

Appendix

Glossary of Climate Technologies | Heavy Industry (1/2)

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Advanced Plastics Recycling	Also known as "chemical recycling," refers to collection of technologies enabling more efficient recycling, with a primary focus on plastics recycling. Recycling solutions are also underway for textiles and batteries.	**1** – Sorting limitations	**1** – Unknown collection, logistics economics	**4.6 Gt CO_2e- Nature**	(6.5 Gt CO_2e addressable emissions by 2050) x (55% recycling rate)	**$120B – Closed Loop Partners** **$40B – McKinsey** **9% vs. 59% - McKinsey**
Concrete CCUS	Chemical reactions to capture CO_2 produced during concrete production. In calcium looping, the CO_2 is separated and then transformed into sustainable synthetic limestone aggregates that make up the concrete. In amine scrubbing, the CO_2 is simply captured, not affecting the cement manufacturing process.	**1** – Partial capture rate	**1** – High costs relative to cement production	**12 Gt CO_2e- IEA**	**(30yrs cumulative emissions)(4% emissions by calcination)** (40% global capacity can install CCS 2020-2050) (80% capture efficiency)	**$40 - $120 /t - IEA** **0-1% today - Industrial Sustainability Analysis Lab** **40-45% 2050 - IEA**
Energy Efficiency	Innovation of existing processes to use less energy in providing the same amount of useful output from a service (e.g., by upgrading motors, fans and heat pumps)	**5** – Variety of efficiency measures implementable today	**5** – efficiency measures use less outputs, achieving costs savings	N/A	N/A	N/A
Fossil Fuel Combustion CCS	Process of capturing CO_2 at both coal and natural gas plant, before it is emitted into the atmosphere, and sequestering it into the ground.	**3** – Power-intensive processes, some of which cannot be retrofitted to older coal plants	**3.5** – Post combustion, chemical absorption at early adoption stage	**4.9 Gt CO_2e- IPCC**	Approximated lower bound IPCC estimate to address specificity of tech among all CCS techs	N/A

Glossary of Climate Technologies | Heavy Industry (2/2)

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Green Steel	Use of electrolytic (green) hydrogen to produce the high heat needed for the direct reduced iron process, which is essential to steel making.	**3** – Ore reduction chemistry not fully optimized	**3** – Availability of electrolytic hydrogen	**12 Gt CO_2e** **Hydrogen Council**	N/A	**$150 /t CO_2e - EDF** **$278B - Bloomberg** **$35 / Mwh; $2.7T - IEA** **4% today - Alcimed** **31% 2050 - Entrepreneur**
Industrial Heat	Substitution of electricity as the primary energy source for industrial heat processes (p to approximately 1,000 degrees Celsius), replacing carbon-emitting energy sources such as coal. Electrification does not require fundamental changes in industrial processes, but merely the replacement of existing equipment (e.g., boiler, furnace) with electric equipment.	**4** – Electric equipment supporting heat processes up to 400 Celsius are commercially available; electric equipment for processes up to 1,000 degrees have been effectively piloted for certain applications	**4** – Until recently, low oil prices have remained a barrier to adoption	**3.9 Gt CO_2e** **EDF MACC**	(260 Mt in 2050)(30 years)(ramp-up reduction factor: 0.5)	N/A
Methane Leakage Detection and Repair (LDAR)	Supplementing of current techniques (on the ground inspections with optical gas-imaging cameras) with continuous monitoring sensors, drones and satellites to maximize efficacy of detecting fugitive methane sources during oil and gas production and transportation	**5** – LDAR technologies proven at scale	**5** – Sale of captured methane outweighs inspection costs (i.e., it would be financial beneficial for O&G producers to implement LDAR)	GWP 100: **12 Gt CO_2e** GWP20: **38 Gt CO_2e** **IEA**	(14.5 Mt CH_4 / year) x (27GWP) x (30 years) = 11.76 Gt CO_2e	N/A

Glossary of Climate Technologies | Buildings

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Alternative Refrigerants	The replacement of hydrofluorocarbons (HFCs) used in a variety of applications by alternative refrigerants with significantly lower global warming potential including ammonia, carbon dioxide, propane, and isobutane.	**4** – Preferred "natural" alternatives each come with trade-offs, including safety, cost, and efficiency considerations	**4** – As a result of the 2016 Kigali Accord, new systems supporting alternative refrigerants are available globally; In some cases, retrofitting existing appliances reduces performance	GWP 100: **40 Gt CO_2e** GWP20: **143 Gt CO_2e** **IEA**	(53 Gt CO_2e 2020-2060) x (0.75) = 39.75 Gt CO_{2e}GWP20 estimated at 2690x by IPCC	**$284B – EPA** **2200 GWP today vs. 150 GWP 2050 - IEA**
Demand Response	Programs enabling buildings to reduce or shift electricity usage during periods of stress or constraint.	**4** – Lack of relevant IT communication tools	**5** – smart control and automation systems enable cost savings	N/A	N/A	N/A
Energy Efficiency	Innovation of existing processes to use less energy in providing the same amount of useful output from a service (e.g., installing rainwater storage systems as water source for green locations).	**5** – Variety of efficiency measures implementable today	**5** – efficiency measures use less outputs, achieving costs savings	N/A	N/A	N/A
Insulation	Any object in a building used as insulation for thermal management. By installing insulation, buildings use less energy for heating and cooling. Related technologies include **dynamic glass** which automatically adjusts the tint level and can block more than 85% of unwanted solar radiation. **Green roofs** provide insulating layer of vegetation on top of residences and commercial properties to reduces energy load and emissions related to heating and cooling buildings. **Cool roofs** use light reflecting materials or paints to reduce heat of roof surface from sunlight.	**5** – Even though a wide number of material and methods exist today that generate significant efficiencies, R&D continues to bring about new efficiency gains	**4** – Many insulation material remain expensive relative to alternatives Assessing and implementing insulation materials and techniques requires skilled architects and engineers, who can be costly and rare	**21 Gt CO_2e** **IPCC**	[2020-2030 (0.88 Gt CO_2e) x (0.4 ramp-up reduction factor) x (20 years)] + [2030-2050 (0.88) x (20 years)]	**40% - GreenBiz** **1% today vs. 100% 2050 – World Green Building Council** **15 months – National Insulation Association** (calculated avg.)

Glossary of Climate Technologies | Transportation

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Battery Electric Vehicles	Vehicles with electric motors powered by energy stored in battery package. They require connection to electrical network to recharge.	**4** – Not yet proven for medium-duty	**3** – Unaffordable to many	**48 Gt CO$_2$e** **Bloomberg New Energy Finance**	(1.6 Gt CO$_2$e / year) x (30 years) = 48 Gt CO$_2$e)	**\$832B** – **Allied Market Research** **\$7.5B** – **Axios** **\$19/t CO$_2$e; \$156/t CO$_2$e** - **EDF** **7.2% today vs. 95% 2050** – **Speed & Scale**
Charging Networks	Infrastructure system of charging stations to recharge battery electric vehicles.	**4** – Issues with reliability and range, slow charging speeds	**4** – Charging infrastructure requires scaling	*Abatement potential not included to avoid double counting with EV's*	N/A	N/A
Clean Shipping	Replacement of fossil fuels with sustainable alternatives to power transport in maritime sector, including ammonia made from green/blue hydrogen (in liquid form or in internal combustion engines), biofuels, hydrogen fuel and fuel cells, and even battery packs.	**3** – Ammonia ignition challenges, relative fuel cell efficiency	**3** – No incentives for prioritization over LNG; hydrogen bunkering network nonexistent	*Abatement potential not included to avoid double counting with sustainable fuel (e.g., clean ammonia, biofuels)*	N/A	N/A
Electric Aviation	Electrifying power supply, storage, and propulsion through solar cells, microwaves, external power cables; batteries, ultracapacitors, and fuel cells; and electric motors, hybrid power, and magnetohydrodynamics (respectively).	**1.5** – Battery density restricts flight range	**1.5** – Prototypes at air taxi level, not commercial passenger	**0.5 Gt CO$_2$e** **Mission Possible Partnership**	N/A	N/A
Energy Efficiency	Innovation of existing processes to use less energy in providing the same amount of useful output from a service (e.g., ongoing increases in miles per gallon ration in passenger vehicles).	**5** – Variety of efficiency measures implementable today	**5** – Efficiency measures use less outputs, achieving costs savings	N/A	N/A	N/A
Fuel Cell Vehicles	Fuel cell vehicles are powered by a fuel (usually hydrogen) that feeds into an onboard fuel cell "stack" that doesn't burn the gas, but instead transforms the fuel's chemical energy into electrical energy. This electricity then powers the car's electric motors.	**3** – Many technologies are in prototype stage; lower lifetime durability than ICE's	**3** - Commercial operation for bus, light-duty vehicles	**13 Gt CO$_2$e** **Hydrogen Council**	N/A	N/A

Glossary of Climate Technologies | Food & Agriculture

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Alternative Proteins	Plant-based and lab-cultured technologies offer protein-rich alternatives to meat products. Behavioral shifts towards alternative proteins will help avoid methane emissions as well as deforestation, saving carbon sinks. With the world population expected to reach 10 billion by 2050, adoption of alternative proteins is imperative to reach NZ50.	**4** – Plant-based techs. proven at scale; commercial-scale pilots for lab-cultured techs	**4** – Availability of plant-based techs. in restaurants and grocery stores for developed countries at a premium; Lab-cultured techs not yet legal in the US	**17 Gt CO$_2$e** **Frontiers**	(0.583 Gt CO$_{2e}$ / year) x (30 years) = 17.49 Gt CO$_{2e}$	1 in 4 – **Gallup** $290B – **BCG** 66% - **Food Navigator USA**
Livestock Methane Inhibitors and Digesters	Methane Inhibitors aim to reduce the methane production of livestock through technologies targeting livestock digestion processes (i.e., enteric fermentation) through feed additives and livestock genomics (breeding). Larger farms can also install anaerobic digesters to treat manure and produce renewable fuel that can be converted and sold as electricity. The benefits of these technologies are dependent on capture of existing manure methane. New manure methane generation and capture require extremely low leakage to result in climate benefits.	**3** - Feed additives can affect animal weight and productivity	**3** - Anaerobic digesters are unaffordable for smaller farms	GWP100: **13 Gt CO$_2$e** GWP20: **42.5 Gt CO$_2$e** **IOPScience**	(53 Tg CH$_4$ manure digesters for pigs + 86 Tg CH$_4$ sheep feed changes and breeding + 349 Tg CH$_4$ cattle feed changes, breeding, digester) x (27 GWP) = 13.18 Gt CO$_2$eGWP20 = 87x	**$400K - $5M – Anaerobic Digestion Community** **25 – 40% - California Air Resources Board**
Precision Agriculture	The process improving crop yields and assisting management decisions using high technology sensors, analysis tools, and satellite-based farm analytics. It ensures the effective management of fertilizers and irrigation processes.	**4** - IoT connection limitations in rural areas	**2** - Lagging adoption due to techs. costs and very-high industry fragmentation	**9.8 Gt CO$_2$e** **WEF**	(0.05% abatement) x (195 Gt CO2e agriculture emissions)	**$40B - $60B; $500B - McKinsey**
Zero-Emission Farm Equipment	Replacement of tractors and combine harvesters using fossil fuels with electric battery vehicles.	**2** – Smaller-sized farm equipment commercially available; reliability and durability of batteries remains an issue (in particular given extended usage)	**2** – Financial incentives required to offset high-capital and encourage early retirement of existing equipment; lack of charging infrastructure	**0.54 Gt CO$_2$e** **McKinsey**	N/A	N/A

Glossary of Climate Technologies | Grid Connectivity

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Other Sources
Load flexibility	The ability to adjust energy usage to accommodate for fluctuating demand. Applications include demand charge management, time-of-use price arbitrage, demand response, and power procurement optimization. Load flexibility will be an important part of the net zero transition narrative as electric vehicles increase grid demand.	**5** – technologies proven at scale; it is up to policymakers and utilities providers to adopt across geographies	**5** – Achieving cost savings in transmission and distribution services through more efficient energy deployment	*Abatement potential not included to avoid double counting with renewables techs*	$14T grid investment – **S&P Global**
Long-distance HVDCs	HVDC (high-voltage direct current) is a high capacity, long-distance transmission system with greater efficiency than HVAC (high-voltage alternating current) transmission systems. Innovations to converters accommodate for renewables variability, allowing for their integration into the grid.	**4** – Ongoing improvements to circuit breakers enabling smoother operation of HVDC grids	**4** – Higher up-front costs, but greater lifetime cost savings compared to HVAC		N/A
Smart Grids	An electricity supply network that uses digital communications technology to detect and react to local changes in usage. It enables **demand response**, the change in the power consumption of electric utility customers – residential or commercial - to better match the demand for power with the supply.	**5** – Technology proven at scale	**4** – Adoption depends on local jurisdictions approval; despite lifetime savings, upfront costs of some “smart” technologies remains a barrier to potential be users (utilities are offering incentives to mitigate)		$15% grid digitalization today vs. 50% in 2050 - **IEA**

Glossary of Climate Technologies | Energy Storage

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Other Sources
Compressed Air	Air compressed into a cavern underground creates energy through a turbine upon release.	**4** – Capable of large scale storage up to 1000 MWe	**4** – High capital costs, lack of awareness by utility planners	*Abatement potential not included to avoid double counting with renewables techs*	N/A
Clean Hydrogen	The process of producing and storing clean hydrogen (as either a gas, a liquid or by absorption within other solids), to be used as fuel, feedstock. Hydrogen can be re-converted into electricity at a later time, creating energy. Includes **green hydrogen** (hydrogen produced by splitting water by electrolysis, producing only hydrogen and oxygen) and **blue hydrogen** (hydrogen produced from natural gas and supported by carbon capture utilization and storage. The CO_2 generated during the manufacturing process is captured and stored permanently underground. The result is low-emissions hydrogen that produces no CO_2).	**3** - Hydrogen is a highly corrosive gas; leakage risks during storage must be addressed	**2** - electrolyzers made from supply chain critical elements		**10GW** today vs. **930GW** 2050 - NREL
Pumped Hydro	Process of pumping water into reservoir at high elevation and harnessing the energy created when the water is released at lower elevation.	**5** – Technology proven at scale	**5** - Possible water loss through evaporation; location dependent (requires difference in height between reservoirs)		N/A
Flywheel	Flywheel convert excess electricity into kinetic energy using a motor to spin a large flywheel and convert it back to electrical energy using a motor as a generator).	**4** – short discharge times require multiple flywheel installations for large scale applications	**4** - need investments in utility-scale units		N/A
Batteries	New generation of batteries that are cheaper, can pack in more energy and charge faster. Enabled by alternative materials and new designs.	**3** – Li-ion alternative chemistries can degrade more quickly upon recharge	**3** – Commercial deployment is fragmented across geographies; high manufacturing costs at R&D stage		**$277B** – BloombergNEF

Glossary of Climate Technologies | Electricity Generation (1/2)

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Geothermal	The process of using heat from the earth's core to heat water or another working fluid. The working fluid is used to turn a turbine of a generator, producing electricity.	**4** - Extraction of geothermal energy releases limited amount of GHG (e.g., hydrogen sulfide, carbon dioxide, methane).	**4** – Location specificity make it hard to scale and high upfront costs remain a barrier	**8.0 Gt CO$_2$e** Source: **IPCC**	{[2020-2030 (0.73 Gt CO2e) (10 yrs)(0.4 ramp-up reduction factor)] + [2020-2050 (0.73)(20yrs)] + [2020-2030 (1.11 Gt CO2e) (10)(0.4)] + [2020-2050 (1.11)(20) (1.5 scaling multiplier)]} /2	N/A
Nuclear	Most established technology is **nuclear fission**, the process of splitting atomic nuclei to power steam turbines that generate electricity. Emerging technologies include **Small Modular Reactors** (SMRs), prefabricated units can be shipped and sited on locations not suitable for larger nuclear power plants, and **nuclear fusion**, the process of combining atomic nuclei to release energy.	**4 –Fission**: tech. proven effectively at scale **2 – Fusion:** A handful of prototype reactors exist, but the first commercial plant isn't expected to be functional before 2035-40 **3 – SMR:** One functioning SMR and 70+ SMRs in development around the world with varied outputs and application	**3 – Fission:** Plants' takes years and increasingly run over budget (e.g., increasing risks regulations) **2 – Fusion:** Pilots already significantly over budget **3 – SMRs:** Offer savings in cost and construction time due to simpler designs, limited customization requirements, and reduced fuel requirements (vs. fission plants)	**45 Gt CO$_2$e** Source: **IPCC**	[2020-2030 (1.32 Gt CO2e) (10 yrs)(0.4 ramp-up reduction factor)] + [2020-2050 (1.32)(20yrs) (1.5 scaling multiplier)]	**658 GW – IEA** **\$107/t CO$_{2e}$ - EDF**
Ocean Wave Power	Process of converting kinetic energy from the motion of ocean waves and tides into electricity through devices acting as underwater wind turbines.	**1** - Novel device prototype testing in real sea conditions	**1** - Most expensive of renewables due to intrinsic design challenges	**11 Gt CO$_2$e** **Ocean Panel**	N/A	N/A
Small Hydropower	The development of hydroelectric power on a scale suitable for local community and industries, or to contribute to distributed generation in a regional electricity grid.	**4** - Tech. effective; requires careful design and installation	**4** - Expanding in remote communities	**5.6 Gt CO$_2$e** **Energy.gov**	N/A	N/A

Glossary of Climate Technologies | Electricity Generation (2/2)

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Solar	The use of the sun's energy using photovoltaic cells in solar panels and transparent photovoltaic glass to generate electricity.	**5** - Full functionality with ongoing enhancements to materials and processes	**4** - Institutional (e.g., inefficient legal frameworks), and technical barriers (e.g., lack of skills to install solar PVs) must be overcome	**134 Gt CO$_2$e** **Nature**	180 Gt CO$_2$e + 12 Gt CO$_2$e (removal of trade barriers) x (0.75 reduction factor for 40 year estimate) = 134	**$57B** (from $280B) – **IEA** **$4.2T** (from $9.5T) – **BNEF** **821TWh** today vs. **23,469TWh** 2050 – **IEA** **$31/t CO$_2$e** - **EDF**
Waste Methane Capture	Anaerobic treatment of municipal and industrial waste to recover methane, which can be transported through pipeline systems as renewable gas that can be converted and sold as electricity.	**5** - 85% efficiency in closed landfills	**4** – Installation costs of gas-to-electricity technologies at landfills	GWP100: **28 Gt CO$_2$e** GWP20: **90.5 Gt CO$_2$e** **IOPScience**	(778 Tg CH4 municipal waste + 262 Tg CH4 Industrial waste) x (27GWP) = 28.08 Gt CO$_2$e GWP20 = 87x	N/A
Wind	The process of collecting and converting the wind's kinetic energy through turbines (onshore or offshore) to generate electricity.	**5** - Full functionality with ongoing expansions in processes (e.g., onshore)	**4** – High upfront and maintenance costs (particularly offshore) remain	**154 Gt CO$_2$e** **MDPI**	N/A	**$223B** (from $280B) **IEA** **$5.3T** (from $9.5T) – **BNEF** **1592TWh** today vs. **24,785TWh** 2050 – **IEA** **$11-40/t CO$_2$e** - **EDF**

Glossary of Climate Technologies | Sustainable Fuels

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Biofuels	Any fuel that is derived from biomass—that is, plant or algae material or animal waste. It includes biokerosene ("Sustainable Aviation Fuel"; SAF) – mixed with aviation kerosene – which is commonly produced from vegetable oils (such as soy), animal fats, and urban waste.	**4** - Innovation needed to increase conversion rates of waste as input	**4** - More expensive than subsidized fossil fuels; limited input with no negative externalities	**22 Gt CO_2e** **IPCC**	{[2020-2030 (0.35 Gt C_{O2}e) (10 yrs)(0.4 ramp-up reduction factor)] + [2020-2050 (0.35)(20yrs)] + [2020-2030 (1.05 Gt CO_2e) (10)(0.4)] + [2020-2050 (1.05)(20) (1.5 scaling multiplier)]} /2	**55Mt** today vs. **750Mt** 2050 – **IEA** **230B gallons** (all jet fuel) - **DOE** **\$33/t CO_2e** - **EDF**
Clean Ammonia	Ammonia produced using green hydrogen (through electrolysis). Used as fertilizer—ammonia's traditional role—or as an energy-dense fuel (more easily stored and transported). It can also be converted back into hydrogen.	**3** - Production via solar power and electrolysis in testing phase	**2** - Early-stage global pilots for functional commercial plants	**10.8** Gt CO_2e **Siemens**	(0.36 Gt CO_2e) x (30 years)	**36 Mt today** (assumes 20% used for transport, since 80% is given for fertilizer usage) **International Center for Sustainable Carbon** vs. **108 Mt by 2050** (conversion of tons to tonnes) **Ammonia Energy Association**
Synfuels	Generic term applied to any manufactured fuel with the approximate composition and comparable specific energy of a natural fuel. Sustainable synfuels use biomass produced by photosynthesis or clean hydrogen. It can be used in internal-combustion engines.	**2** - Technical difficulty in scaling MW capacity of pyrolysis plants	**1** - Signed offtake agreements with airlines but not viable without policy support	**3.8** Gt CO_2e **IEA**	N/A	**168 Gt/CO_2e** **EDF MAC**

Glossary of Climate Technologies | Carbon Removal

Technology	Description	Tech. Feasibility	Commercial Viability	Est. Abatement Potential (2020-2050)	Calculation Methodology	Other Sources
Direct Air Capture (DAC)	Extracts CO_2 directly from the atmosphere. The CO_2 can be permanently stored in geological formations or be used, for example, in food processing (e.g., to carbonate beverages) or combined with hydrogen to produce synfuels. However, to maximize climate benefit, most captured CO_2 will need to be sequestered, thereby achieving negative emissions (if properly managed, geological storage can retain 99% of sequestered CO_2 for over 1,000 years).	**3** - More large-scale demonstrations are needed to refine the technology and reduce the risks of CO_2 storage	**2** - Higher cost and energy needs than other sequestration methods due to lower atmospheric concentration of CO_2)	**20 Gt CO_2e** **IEA**	(85 Mt CO_2/yr by 2030)(10) + (980 Mt CO_2/yr by 2050)(20)	**$250-600 - WRI** **$129M - WRI** **40 Mt** *today vs.* **980 Mt - IEA**
Enhanced Rock Weathering	Accelerates natural process of rock weathering (natural process where CO_2 in rainwater reacts with rocks and is then locked away in carbonate form for over 100,000 years) by crushing rock into rock dust, increasing surface area and thereby causing weathering process to happen faster (and accelerate sequestration of CO_2 into rock).	**1** -Uncertainty around soil weathering rates and land-ocean transfer of weather products	**1** – Deployment is not considered viable in near-term	**15 Gt CO_2e** **Nature**	(0.5 Gt CO_2e / year) x (30 years)	N/A

Endnotes

1 **"The latest IPCC report unpacks the role of innovation. Here are five key takeaways."**
Environmental Defense Fund, April 15, 2022

2 **"Clean energy innovation needs faster progress,"** IEA

3 BAU Scenario uses **IPCC emissions scenario** where policies existing today are projected to 2050, assuming no further policy support

4 Graphic uses emissions data as calculated by Project Drawdown's "Scenario 1." While Drawdown does not explicitly cite GWP numbers it used for methane abatement solutions in its technical summaries, it can be assumed that GWP is around 27-30 (using 100-year range). Drawdown cites the GWP of current refrigerants as in the 2000s. Since the analysis in this report was conducted, the Inflation Reduction Act (IRA) has been signed into law. While this will change the landscape for clean energy and climate in the U.S., the guidance presented here around for how companies should think about innovation and where they should prioritize action is still germane in this changing environment

5 **"Covid-19, Crypto, and Climate**, Chapter 3: Investment Funds: Fostering the Transition of a Green Economy," International Monetary Fund, October 2021.

6 Technologies shown represent prominent examples for each sector and are not an exhaustive list

7 Carbon capture technologies exist in a variety of sectors, but for the purposes of this visual refers to industry-agnostic removal mechanisms

8 **"Wind turbine blades can't be recycled, so they're piling up in landfills."** Bloomberg. February 2020

9 "**Save money with solar energy for your business."**
The Balance, June 25 2019

10 **"Towards underground hydrogen storage: A review of barriers,"** ScienceDirect, July 2022

11 Biofuels can be considered high-integrity when they credibly reduce emissions, adhere to strong environmental and social safeguards, and are accurately accounted for to avoid double-counting of emissions reductions. High-integrity biofuels should have zero or very low risk of causing indirect land-use changes, meaning they do not divert edible crops or land used to grow food, and do not contribute to deforestation or habitat destruction. Their production should respect human rights, land rights and water rights, and should contribute to the UN's Sustainable Development Goals

12 In 2020, $472B in explicit subsidies were allocated to coal, oil and natural gas globally

13 Asterisks in visual refer to climate technologies for which clean hydrogen is a direct input. Clean hydrogen as a technology itself is not included as a visual bubble to avoid duplication

14 CO_2 equivalent estimates are used since GHGs have varying levels of global warming potentials (GWPs). Methane and hydrofluorocarbons (used in refrigerants) linger in the atmosphere for a shorter duration compared to CO_2, but trap much more heat per weight, making their abatement particularly urgent in the near-term. GWP100 (i.e., over 100 years) used for methane is 27x CO_2; GWP100 used for today's refrigerants is 2200x CO_2; GWP20 values for both are included in Appendix

15 Bubble sizes show relative magnitudes of abatement potential within each sector

16 Technology innovation lifecycle stages adapted from **IEA's extended Technology Readiness Level (TRL) scale**

17 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"**
Figure TS.6 in IPCC AR6 WGIII

18 **"Cement and concrete as an engineering material: A historical appraisal and case study analysis."**
ScienceDirect, May 2014

19 **"CCS at Norcem Brevik: Background,"** Norcem

20 Additionally, CCUS abatement potential does not account for transport of captured CO_2

21 Clinker is a binder material produced in the kilning stage of cement production, responsible for the majority of **cement's costs and emissions**

22 **"Iron and Steel Technology Roadmap,"** IEA, October 2020

23 Any DRI process will result in emissions unless it uses electrolytic (green) hydrogen, meaning blue hydrogen DRI must be equipped with carbon capture capabilities to be considered a sustainable alternative

24 The CCUS method most commonly used in DRI is chemical adsorption. Physical adsorption is expected to be a less costly CCUS technique but requires more pilot projects for DRI applications

25 **"Iron and Steel Technology Roadmap,"** IEA, published in October 2020 Technology report

26 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"** Figure TS.6 in IPCC AR6 WGIII

27 **"IPCC includes GWPs for Hydrocarbons in New Report,"** Hydrocarbons21, August 2021

28 **"Alternative Refrigerants,"** Project Drawdown

29 **"Have we reached the tipping point for CO2 refrigeration systems?"** Henderson Engineers, June 2020

30 A net zero building earns its title by producing enough renewable energy to meet its annual energy consumption requirements. This can be done through a variety of efficiency measures in addition to insulation, including water conservation and digitization to optimize space management

31 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"** Figure TS.6 in IPCC AR6 WGIII

32 **"Charting the course for early truck electrification,"** RMI, 2022

33 **"A severe EV battery shortage could happen in less than 3 years,"** PR Newswire, May 2022

34 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"** Figure TS.6 in IPCC AR6 WGIII

35 **"Everything you need to know about agricultural emissions,"** World Resources Institute, May 2014

36 Potency refers to a greenhouse gases' global warming potentials (GWPs), in this context over a 100-year period

37 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"** Figure TS.6 in IPCC AR6 WGIII

38 **"Innovative Foods: a guide to responsible investment in cell-cultured meat and seafood,"** Environmental Defense Fund + Business

39 **"Carbon removal 'unavoidable' as climate dangers grow, new IPCC report says,"** Scientific American, April 2022

40 See Appendix for data sources and calculation methodology

41 **"Carbon Sequestration,"** Britannica: "It is estimated that properly managed geological storage is very likely (90% probability) to retain 99% of its sequestered carbon dioxide for over 1,000 years."

42 **"Direct Air Capture,"** IEA, November 2021

43 **"6 Things to Know about Direct Air Capture,"** World Resources Institute, May 2022

44 **"Total anthropogenic direct and indirect GHG emission for the year 2019 (in GTCO2eq) by sector and sub-sector,"** Figure TS.6 in IPCC AR6 WGIII

45 **"5 Fast Facts About Nuclear Energy,"** Office of Nuclear Energy, March 2021

46 **"3 reasons why nuclear is clean and sustainable,"** Office of Nuclear Energy, March 2021

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