RethinkX

Disruption, Implications, and Choices

Rethinking Climate Change

How Humanity Can Choose to Reduce Emissions 90% by 2035 through the Disruption of Energy, Transportation, and Food with Existing Technologies

A RethinkX Disruption Implications Report

August 2021

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The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

We analyze the impacts of disruption, sector by sector, across the economy. We aim to produce analyses that reflect the reality of fast-paced, technology disruption S-curves. Mainstream analysts produce linear, mechanistic, and siloed forecasts that ignore systems complexity and thus consistently underplay the speed and extent of technological disruption – for example solar PV, electric vehicles, and smartphone adoption. By relying on these mainstream forecasts, policymakers, investors, and businesses risk locking in inadequate or misguided policies and investments, resource misallocation and negative feedbacks that lead to massive wealth, resource, and job destruction as well as increased social instability and vulnerability.

We take a systems approach to analyze the complex interplay between individuals, businesses, investors, and policymakers in driving disruption and the impact of this disruption as it ripples across the rest of society. Our methodology focuses primarily on market forces that are triggered by technology convergence, business model innovation, product innovation, and exponential improvements in both cost and capabilities.

Our aim is to inspire a global conversation about the threats and opportunities of technology-driven disruption and to focus attention on choices that can help lead to a more equitable, healthy, resilient, and stable society.

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With Thanks

Thanks also to Morry Cater and the team at Cater Communications, and to the design team at Lokate Design.

Our thanks in no way implies agreement with all (or any) of our assumptions and findings. Any mistakes are our own.

Preface

RethinkX uses the Seba Technology Disruption Framework to model and forecast technology disruptions. The analysis in this report is based on detailed evaluation of data on the market, consumer, and regulatory dynamics that work together to drive disruption in the energy sector. We present an economic analysis based on existing solar photovoltaic, onshore wind, and lithium-ion battery technologies that have well-established cost curves, and on existing business models. We extrapolate data where we have credible insight into how these cost curves will continue in the near future. The disruption we analyze in this report could actually happen more quickly than we project if there is an acceleration of the cost curves, a breakthrough in the underlying technologies, or business-model innovations that bring the disruption timeline forward.

Our findings and their implications are based on following the data and applying our knowledge of finance, economics, technology adoption, and human behavior. Our findings show the speed, scale, and implications of the disruptions that we expect to unfold in a rational context. Scenarios can only be considered in terms of probabilities. We think the scenario we lay out in this report is far more probable than those currently forecast by others. Our aim is to provide insights that decision-makers can utilize to benefit society.

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This report includes possible scenarios selected by the authors. The scenarios are not designed to be comprehensive or necessarily representative of all situations. Any scenario or statement in this report is based upon certain assumptions and methodologies chosen by the authors. Other assumptions and/or methodologies may exist that could lead to other results and/or opinions.

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Executive Summary

Technology disruptions already underway in the energy, transportation, and food sectors have extraordinary implications for climate change. These three disruptions alone, driven by just eight technologies, can directly eliminate over 90% of net greenhouse gas (GHG) emissions worldwide within 15 years. Market forces can be leveraged to drive the bulk of global GHG emissions mitigation because the technologies required are either already commercially available and competitive today, or can be deployed to market before 2025 with the right societal choices. The same technologies will also make the cost of carbon withdrawal affordable, meaning that moonshot breakthrough technologies are not required to solve the 'Last Carbon Problem' and go beyond net zero from 2035 onwards.

Our previous research has shown that disruptions of the energy, transportation, and food sectors are inevitable. Solar, wind, and batteries (SWB) will disrupt coal, oil, and gas. Autonomous electric vehicles (A-EVs) providing transportation-as-a-service (TaaS) will disrupt internal combustion engines and private vehicle ownership. And precision fermentation and cellular agriculture (PFCA) will disrupt meat, milk, and other animal products. The three disruptions are already unfolding simultaneously, and their implications for climate change are profound. Yet it will be up to us to decide whether or not we deploy these technologies worldwide rapidly enough to avoid dangerous climate change.

The greatest barrier to fighting climate change is therefore our mindset. Conventional thinking views emissions mitigation through a linear, reductive lens that fails to appreciate the character, speed, and dynamics of change in both natural systems and human systems. By failing to fully appreciate these systems dynamics, conventional models have tended to underestimate not only the threat of climate change itself, but also the potential of technology to address it. As a result, we have seen a consistent pattern of mistakes and corrections over time, where each year the underestimated threat of climate change is corrected in the direction of 'worse than we originally thought' while the underestimated potential of technology to address it is corrected in the direction of 'better than we originally thought'. Conventional thinking has therefore wasted time, attention, and resources on an eclectic array of 'Band-Aid' approaches to solving climate change like subsidies and taxes, biofuels, clean coal, clean diesel and other superficial techno-fixes that merely treat symptoms rather than the underlying problem.

Instead, a simpler and more effective approach is to focus on a handful of key technologies that will transform the entire foundation of our economy. But simple does not mean easy. Simple means we understand the key drivers and levers of major systemic change. However, there are many obstacles to overcome, and we cannot afford to be complacent. Despite the tremendous opportunities that the clean disruption of energy, transportation, and food will bring, technology alone is not enough. Societies around the world must make the right choices. We can either accelerate the disruptions and solve the climate crisis by ushering in a new era of clean prosperity, or we can waste precious time and trillions of dollars propping up the incumbent system with an ineffective 'all-of-the-above' approach that exposes humanity to additional risk of climate change impacts.

In this report, we help decisionmakers understand these choices by categorizing sources of emissions according to three stages of mitigation readiness: Research, Deploy, and Scale. More than three quarters of global GHG emissions can be mitigated by just eight key technologies that are either already at market and able to scale immediately, or ready to begin deploying to market. This provides a guide for decision-making based on how to prioritize our efforts to maximize mitigation benefits as soon as possible. Without such a framework, decisionmakers are left with a scattershot rather than focused approach to fighting climate change, which runs the risk of misallocating financial, material, and political resources.

To maximize the climate benefits of these disruptions, investors, policymakers, civic leaders, and other decisionmakers should focus attention and resources in direct proportion to where the fastest and most impactful opportunities for emissions mitigation are located. Since the overwhelming majority of these opportunities already lie in the Deploy and Scale stages, our primary efforts should be on enabling economic forces to do the heavy lifting by ensuring open, competitive, and transparent markets. This means removing barriers that favor the incumbents such as utility monopolies in the energy sector, removing regulatory hurdles to electric and autonomous vehicles in the transportation sector, and removing livestock farming subsidies and protections in the food sector.

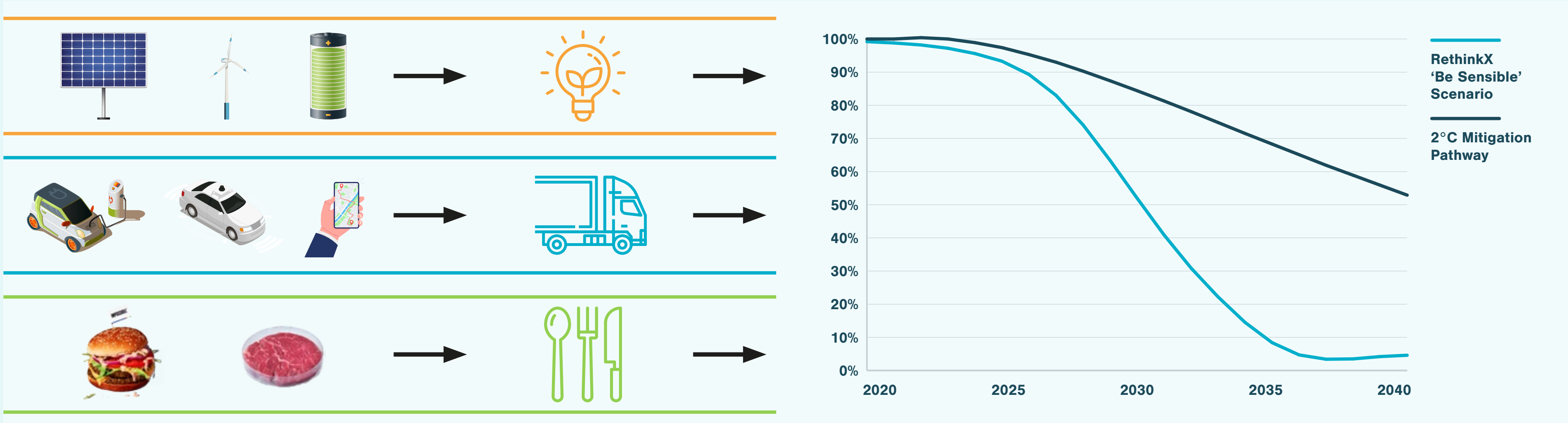
Regions, nations, cities, communities, businesses, and investors choosing to embrace and lead the disruptions rather than resist them will reap enormous economic and social rewards as well as environmental benefits. Some may choose to lead the disruptions in order to capture the extraordinary economic benefits, or to mitigate dependence on imported fragile food and energy supplies, while others may do so because of the political capital to be gained. As different actors seek to accelerate the disruptions in their own context to avoid risks or secure advantages, the ensuing race to the top will generate further powerful accelerating feedbacks that will compound the speed and scale of disruptions worldwide. Moreover, the clean technologies are inherently decentralizable and democratizing, and will therefore allow less-developed areas to leapfrog over previous barriers to human development, lift their disadvantaged populations into prosperity, and level the playing field between rich and poor economies.

Although reaching net zero emissions will not solve the problem of climate change entirely on its own, it represents a huge step in the right direction. The same technologies that make these dramatic emissions reductions possible will also make carbon withdrawal at the gigaton scale feasible. The combination of superabundant clean energy, electric and autonomous vehicles and machines, and billions of hectares of land freed from animal agriculture, will transform the economics of both reforestation and technology-based carbon withdrawal. This makes the three disruptions doubly essential for achieving a complete climate change solution.

By supporting the clean disruption of energy, transportation, and food, societies can choose to accelerate global greenhouse gas mitigation to reach net zero emissions before 2040 and lay the groundwork for a complete solution to climate change, simultaneously saving trillions of dollars and improving prosperity and quality of life worldwide. But to do so, we must escape the confines of the conventional mindset and rethink what is possible through a larger lens that captures the full complexity of disruption.

Box 1: Key Findings

Figure 1: Eight Technologies, Three Disruptions, and 90% Emissions Reduction by 2035



Source: RethinkX.

Key Implications of the Energy, Transportation, and Food Disruptions for Climate Change

1. We can achieve net zero emissions much more quickly than is widely imagined by deploying and scaling the technology we already have.
2. We can achieve net zero emissions without collateral damage to society or the economy.
3. Markets can and must play the dominant role in reducing emissions.
4. Decarbonizing the global economy will not be costly, it will instead save trillions of dollars.
5. A focused approach to reducing emissions is better than an all-of-the-above 'whack-a-mole' approach.
6. We no longer need to trade off the environment and the economy against each other.
7. The clean disruption of energy, transportation, and food will narrow rather than widen the gap between wealthy and poor communities, and developed and less-developed countries.
8. The same technologies that allow us to mitigate emissions will also enable us to withdraw carbon dioxide from the atmosphere affordably.
9. Societal choices matter, and technology alone is not enough to achieve net zero emissions.

Part 1:

RethinkX Greenhouse Gas Emissions Scenarios

We present three scenarios in this analysis: the Core Disruption Scenario ('Be Sensible'), the Accelerated Disruption Scenario ('Get Serious'), and the Delayed Disruption Scenario ('Get Stuck'). These scenarios represent a plausible spectrum of greenhouse gas emissions pathways that are determined by the societal choices we make. Although disruptions of the energy, transportation, and food sectors are inevitable for purely economic reasons, it is possible to either accelerate or delay the disruptions and their associated emissions mitigation with good or bad choices.

The Limits of Conventional Thinking

Conventional thinking about emissions mitigation and the scenarios based on them lack an adequate understanding of the nature, speed, and dynamics of change in both earth systems and human systems. As a result, conventional analyses often examine both problems and solutions through a narrow, linear lens that overlooks the systemic complexity driving change (see Box 2: Mistakes of Conventional Forecasting). By failing to fully appreciate these systems dynamics, these analyses have tended to underestimate not only the threat of climate change itself, but also the potential of technology to address it. As a result, we have seen a consistent pattern of corrections over time, where each year the estimated threat of climate change is corrected in the direction of 'worse than we originally thought' while the estimated potential of technology to address it is corrected in the direction of 'better than we originally thought'.[a]

The disruption of the horse by automobiles, of film cameras by digital cameras, of landlines by smartphones, along with dozens of other historical examples show that disruptive technologies do not follow a pathway of slow, incremental change, but instead grow exponentially because of feedback loops embedded in economic forces (see Box 4: The Surprising Speed of Disruption). The declining costs and improving capabilities of the new technologies make incumbent industries economically uncompetitive, sending them into a death spiral of increasing costs and diminishing returns. History shows that disruptions tend to render previous technologies obsolete within just 10-15 years.

The conventional approach to emissions mitigation has ignored these dynamics and has instead tried to decarbonize our global economy incrementally through a wide variety of techniques, policies, and technologies.[1] This unfocused, 'whack-a-mole' approach attempts to mitigate each source of emissions in isolation – much like treating the symptoms of a disease rather than its underlying cause. After nearly three decades of failure, and with emissions continuing to rise, the results are discouraging. A far better approach is to focus on the technological disruption of the three foundational sectors of the global economy that are together responsible for over 90% of greenhouse gas emissions: energy, transportation, and food.

It follows that conventional scenarios are implausible because they are based on a fundamental misunderstanding of technology and disruption (see Box 2: Mistakes of Conventional Forecasting). For this reason, none of the scenarios we present in this report are directly comparable to 'Business-as-Usual' or other conventional emissions pathways.

Rethinking Emissions Pathways Through the Lens of Disruption

RethinkX has been consistently more accurate in forecasting technological change than conventional analysts. Our team has accurately predicted the dramatic nonlinear cost improvements and market growth of solar, wind, and batteries (SWB) in the energy sector, autonomous and electric vehicles (A-EVs) together with transportation-as-a-service (TaaS) in the transportation sector, and precision fermentation and cellular agriculture (PFCA) in the food sector.[2,3,4] Our research shows that the energy, transportation, and food sectors are each currently experiencing a technology disruption that will render their incumbent industries obsolete within 15 years – much faster than most conventional analyses have projected (see Part 2: The Disruption of Energy, Transportation, and Food for details).

The combined impacts of the energy, transportation, and food disruptions will open up unprecedented opportunities to mitigate carbon emissions and draw down carbon from the atmosphere. Yet although these disruptions are now inevitable, their exact timeline – and thus our exposure to climate change risks – still depends on our societal choices. In this report we present three scenarios for how these choices can play out.

Box 2: Mistakes of Conventional Forecasting

A Mindset Problem

At the heart of humanity's climate change challenge is a mindset problem that overlooks the nonlinear nature, speed, and dynamics of change in both earth systems and human systems. As a result, we often examine both problems and solutions through a linear, reductive lens that fails to recognize the complex systems dynamics driving change.

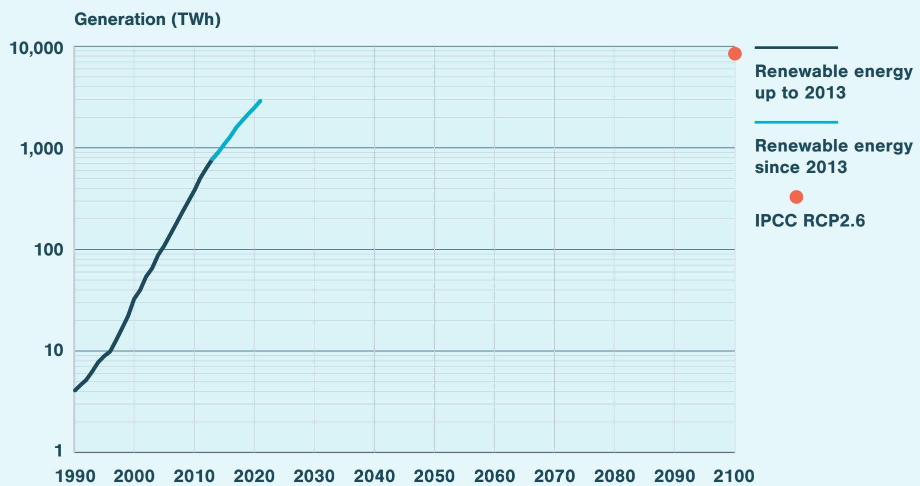
The history of technology disruptions shows that long periods of technological stability are punctuated by abrupt systemic transformations, and often trigger rapid economic and social transformation.[5] Disruption occurs when a new technology of equal or greater capability becomes available at a significantly lower cost than existing alternatives, after which the incumbent technologies are replaced very swiftly, with market share of the new technology rapidly growing from 10% to 90% or more, often within as little as 15 years. This pattern holds for dozens of historical disruptions across all sectors and industries.

Conventional analyses and scenarios also tend to ignore second-order effects that ripple throughout the economy and society, and therefore fail to anticipate the scope of societal impact. Technologies with equal or greater capability at a lower cost tend to expand market size, create new business models, and in many cases generate entirely new markets. As a result, the speed, scale, and impact of technology disruptions is widely underestimated. Only by letting go of linear thinking, and recognizing the real risks and opportunities through a new lens, will we be able to see that the possibilities presented by currently unfolding technology disruptions offer a pathway to solve the climate challenge far faster and more comprehensively than conventionally believed possible (see Appendix B for further detail on RethinkX's disruption framework).

Grave Consequences

In 2014, 5 years after RethinkX co-founder Tony Seba published his first analysis of the exponential growth of solar, the IPCC 5th Assessment RCP2.6 'best case' scenario still assumed that solar, wind, and geothermal power combined would provide only 4% of the world's energy by the year 2100. With no explanation or justification, RCP2.6 and other conventional scenarios simply ignored the exponential trend that was already clear in the data available at the time. The exponential trend has continued since then, and is on target to exceed the RCP2.6 estimate for 2100 before 2030, 70 years ahead of the conventional forecast (Figure 2).[6]

Figure 2: IPCC RCP2.6 Renewable Energy versus Reality (logarithmic plot)*



Source: BP, IPCC, van Vuuren et al., 2011a, van Vuuren et al., 2011b.[7,8,9,10]
** Solar, wind, and geothermal energy combined, excluding hydro power.*

New climate scenarios being developed for the IPCC 6th Assessment, called 'Shared Socioeconomic Pathways' or SSPs, repeat the same errors based on a fundamental misunderstanding of technological change. The only technology-centric scenario, SSP5, is named "Fossil-Fueled Development", and is described as one in which "rapid technological progress" is "coupled with the exploitation of abundant fossil fuel resources".[11] This 'Business-as-Usual' premise fails to understand the fact that the faster technological advancements occur (like the ones driving the disruption of energy, transportation, and food), the less fossil fuels will be utilized over the course of the 21st Century.

False Solutions

The prevailing climate change narrative assumes that we must mitigate emissions within the incumbent energy, transportation, and food system – an approach that cannot solve the problem even in principle, as those unsustainable pollution dynamics are intertwined with incumbent modes of production. As a result, this misguided approach emphasizes behavior change and superficial techno-fixes like clean coal that are merely 'Band-Aids' treating symptoms rather than the underlying disease. Like medieval doctors prescribing bloodletting, these treatments won't solve the problem, they will make actually solving the problem harder, and they will create new problems in the meantime.

We cannot possibly reduce production and consumption to zero, and getting even halfway there would cause unimaginable human suffering, disproportionately impact poor communities and less-developed nations, and wipe out the financial, social, and political capital required to build a truly sustainable energy, transportation, and food system based on clean technology. By focusing on symptoms rather than root causes, conventional approaches to fighting climate change through austerity are not just futile but actively counterproductive. We cannot solve climate change by making our existing system 'less bad', we can only solve it by disrupting and transforming the system itself.

Misconceptions

» We do not need to wait decades or spend hundreds of billions of dollars in a desperate bid to develop unproven breakthrough technologies – instead, we already have the technologies necessary to achieve net zero emissions within 20 years, which will lay the groundwork to drawdown the existing stock of atmospheric carbon using a combination of natural and technological solutions that will only become viable after the disruptions.

» We will not need to pay an extravagant green premium to reduce emissions – instead, investing in the disruptions will save societies trillions of dollars because the disruptive technologies will be much cheaper than the older ones, and much of the deployment can be driven by removing barriers to market forces rather than onerous state interventions.

» We will not need to impose a severe carbon tax on incumbent industries to force them to go clean – instead, the new technologies will economically outcompete the old ones and wipe out any industry that fails to adapt through market forces alone if barriers to market entry and competition are removed.

» We will not need to impose restrictions on personal consumption, which is economically nonsensical and will lead to harmful socioeconomic outcomes – instead, the disruptions will allow us to both eliminate our carbon footprint and bring a high quality of life to everyone on the planet.

» We will not need to pick winners and losers among nations – instead, the disruptions will allow lower-income countries to leapfrog over previous resource-based barriers to human development without a zero-sum tradeoff between the economy and the environment.

» We will not need to solve equity challenges within the strictures of the existing system – instead, the technology disruptions will enable decentralized rather than centralized production of energy, transportation, and food. This can empower local communities to build economic, social, and governance capacity from the bottom-up rather than relying on top-down decision-making and resource allocation from the state. At the same time, existing disadvantages of geography may be turned on their head, as the year-round abundance of sunshine in the tropical and equatorial regions translates into lower costs and competitive advantage throughout the value chains of virtually every industry.

RethinkX Emissions Scenarios

Each of our scenarios presents an emissions pathway from now through 2040. We construct these pathways by estimating the aggregate impact of each disruptive technology on all major sources of greenhouse gas emissions, categorized by sub-sectors of the global economy as shown in Table 1. Each sub-sector therefore has its own emissions mitigation S-curve, shown in Table 3 in Appendix C. We also estimate carbon withdrawal from both active and passive reforestation according to biome, shown in Table 4 and Table 5 in Appendix C. Quantities of mitigation and withdrawal are scaled relative to the initial year of 2020, for which we assume 50 gigatons of net CO_2 equivalent (CO_2e) emissions, and are reported as a percentage. Mitigation of CO_2e emissions across all sub-sectors is then collectively summed together with carbon withdrawals (negative emissions) to produce the final emissions pathway for each of our three scenarios. Any CO_2e emissions that remain after 2040 represent niche industries and markets for which no currently foreseeable technology offers a path to full decarbonization.

For each scenario, the projected emissions pathway is a function of how rapidly we expect the disruption of energy, transportation, and food to translate into a reduction in greenhouse gas emissions, combined with the amount of carbon withdrawal we expect to occur. We assume that passive and active reforestation only occurs on land freed up by the food disruption, and not on any other land area that might also be available for reforestation or afforestation. We also assume no additional carbon withdrawal in the oceans from the disruption of commercial fisheries and the recovery of marine ecosystems.[b]

For additional detail about our methodology, see Appendix C.

The RethinkX Core Disruption Scenario: 'Be Sensible'

In this scenario, societies choose to embrace rather than resist the disruption of the energy, transportation, and food sectors over the course of the 2020s. This simply means responding rationally to economic incentives and removing barriers to the deployment and scaling of SWB, A-EVs and TaaS, and PFCA technologies. Yet this still requires critical societal choices, particularly by governments who can remove barriers to the three disruptions by streamlining market design, breaking up rent-seeking utility monopolies, ensuring that individuals have the rights to produce energy, transportation, and food services, and shutting down further subsidies and public investments into doomed incumbent fossil fuel, legacy road transportation, livestock, and commercial fishing industries whose assets will be stranded by the disruptions.

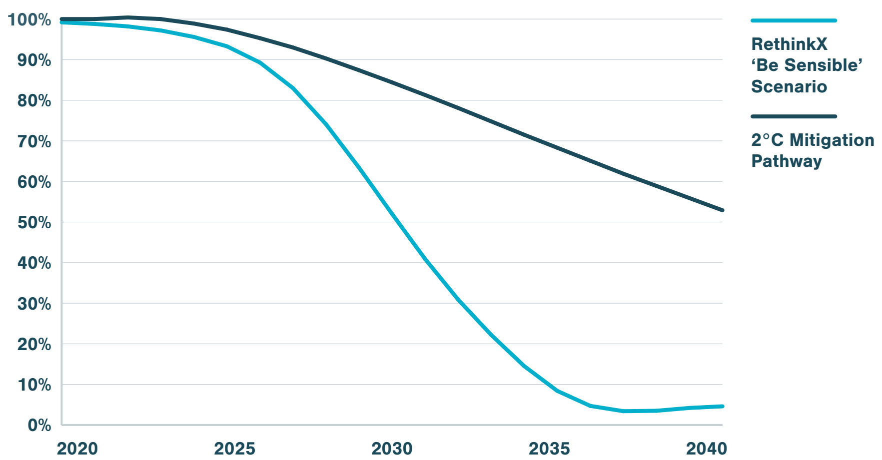
This scenario requires only investments that have a positive economic return, and therefore does not include public expenditures on active reforestation or other carbon withdrawal technologies such as ocean alkalinity enhancement (OAE) and direct air carbon capture and storage (DACCS) (see Box 3: Going Below Zero Emissions). Carbon withdrawal (i.e. offsets) through passive reforestation from the natural recovery of 2.7 billion hectares of land freed up from animal agriculture by the food disruption are included in this scenario, because these withdrawals are costless and inevitable unless that land is actively degraded.

Figure 3 shows the RethinkX 'Be Sensible' scenario compared to the median 2°C pathway through 2040.[c] This scenario reflects the direct implications of our previous research into the disruption trajectories for the energy, transportation, and food sectors, and their impacts on greenhouse gas emissions.

Key features of this scenario include the following:

- Net global emissions decline over 90% by 2035, as a result of the combination of direct mitigation from the three disruptions plus offsets from passive reforestation.
- The disruption of energy, transportation, and food directly mitigates 40% of global emissions by 2030, over 70% by 2035, and over 80% by 2040.
- The 2.7 billion hectares of land freed up from animal agriculture by the food disruption offsets almost 10% of global emissions annually by 2030, and 20% by 2035 and thereafter through the natural (and costless) recovery process of passive reforestation.
- There is no reliance on non-market emissions offsets (i.e. either active reforestation or technology-based carbon withdrawal) that would require government support.
- Emissions remain below the median 2°C pathway throughout the entire time period, meaning that no carbon withdrawal is required to recoup carbon budget lost to overshoot.

Figure 3: The RethinkX Core Disruption Scenario: 'Be Sensible'



Sources: IPCC, Our World in Data, Global Carbon Project, RethinkX.[12,13,14,15]

The RethinkX Accelerated Disruption Scenario: 'Get Serious'

In this scenario, societies choose to get serious and proactively accelerate the disruption of the energy, transportation, and food sectors over the course of the 2020s. Similar societal choices are made to deploy and scale SWB, A-EVs and TaaS, and PFCA technologies in this scenario as in the 'Be Sensible' scenario, with the more aggressive implementation bringing the timeline forward by 1 year. In addition, societies also choose to invest in actively reforesting 20% of the land freed up from animal agriculture by the food disruption (with the remaining 80% of freed land undergoing passive reforestation due to natural recovery), as well as in other carbon withdrawal technologies such as ocean alkalinity enhancement (OAE) and direct air carbon capture and storage (DACCS) (see Box 3: Going Below Zero Emissions).

Key features of this scenario include the following:

» Global emissions decline over 60% by 2030, and 100% before 2035.

» After 2040, global emissions are -20%, or 10 gigatons CO_2e net carbon drawdown per year from the combination of disruption, reforestation, and technology-based carbon withdrawal.

» Global emissions mitigation is a result of the disruption of energy, transportation, and food combined with offsets from active reforestation and technology-based carbon withdrawal.

» Both market forces and public investment are used to drive emissions down.

» Active reforestation is undertaken on 20% of the land freed up by the food disruption, while the remaining 80% undergoes passive reforestation.

» Active reforestation costs vary by biome, ranging from $500 per hectare to $2500 per hectare, with the cost per ton of CO_2e withdrawn averaging just over $10 on a 25-year timeframe.

» The total cost for active reforestation on a 25-year timeframe is $517 billion, or an average of $21 billion per year.

» Active and passive reforestation together offset roughly 20% of emissions, or 10 gigatons CO_2e carbon per year, from 2035 onward.

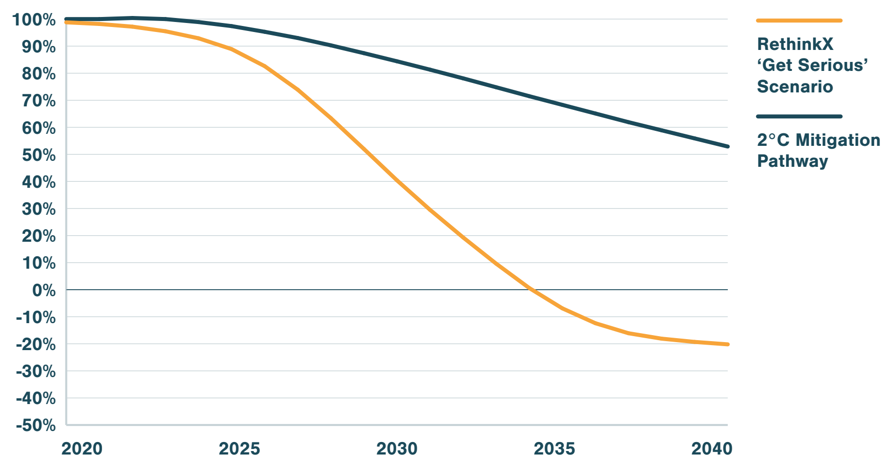
» Technology-based carbon withdrawal ramps up on an S-curve to eventually reach an annual withdrawal rate equivalent to 20% of 2020 emissions, or 10 gigatons CO_2e per year, from 2040 onward.

» The cost of technology-based carbon withdrawal starts at $100 per ton CO_2e but declines to $10 by 2040 on an S-curve, driven by disruption and scaling.

» The total cost for technology-based carbon withdrawal on a 25-year timeframe is $1.1 trillion, or an average of $44 billion per year.

This scenario is illustrated in Figure 4.

Figure 4: The RethinkX Accelerated Disruption Scenario: ‘Get Serious’



Sources: IPCC, Our World in Data, Global Carbon Project, RethinkX.[12,13,14,15]

The RethinkX Delayed Disruption Scenario: ‘Get Stuck’

In this scenario, societies actively resist adopting SWB, A-EVs and TaaS, and PFCA technologies by attempting to protect incumbent fossil fuel firms, utility monopolies, legacy automotive manufacturers, and the livestock and fishing industries from disruption. This effort is ultimately futile, but it does delay the disruption of the energy, transportation, and food sectors by 5 years.

While the three disruptions will still wipe out incumbent industries based on older technologies and reduce emissions accordingly, this scenario illustrates how delays resulting from poor societal choices (i.e. those that resist the new technologies and prop up the incumbencies) would cause us to temporarily exceed the median 2°C pathway, exposing the planet to serious climate change risk.

Importantly, this scenario does not correspond to ‘Business-As-Usual’ (BAU) or any other conventional scenario. Instead, it shows that conventional projections which assume the continued existence of incumbent carbon-intensive energy, transportation, and food industries out to 2100 are not plausible because they fail to recognize the inevitability of disruption.

Key features of this scenario include the following:

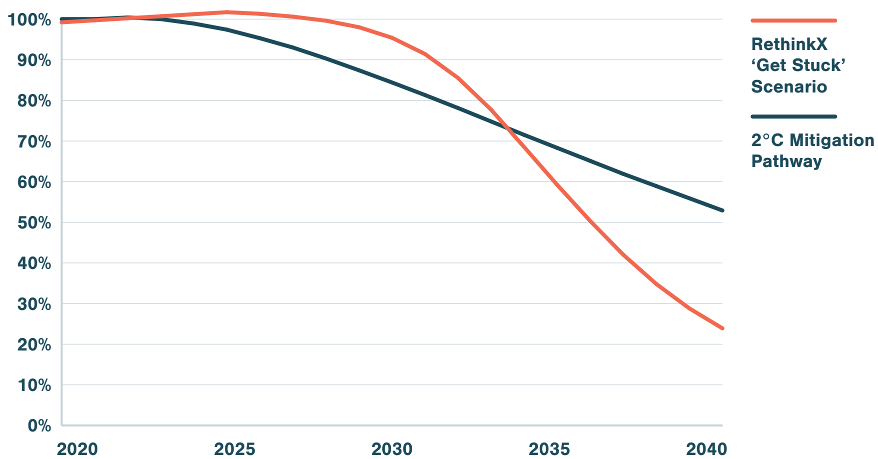
» Emissions continue to rise until 2026, and are still at 95% of 2020 levels in 2030, meaning that they temporarily exceed the median 2°C pathway during the 2020s, placing humanity within the climate danger zone.

» Emissions decline 40% by 2035 and 75% by 2040 as incumbent industries collapse, but this may not be sufficient to avoid serious climate change risks.

» Emissions exceed the median 2°C pathway until the mid-2030s, meaning that net negative emissions achieved through carbon withdrawal will be required to recoup carbon budget lost to overshoot.

This scenario is illustrated in Figure 5.

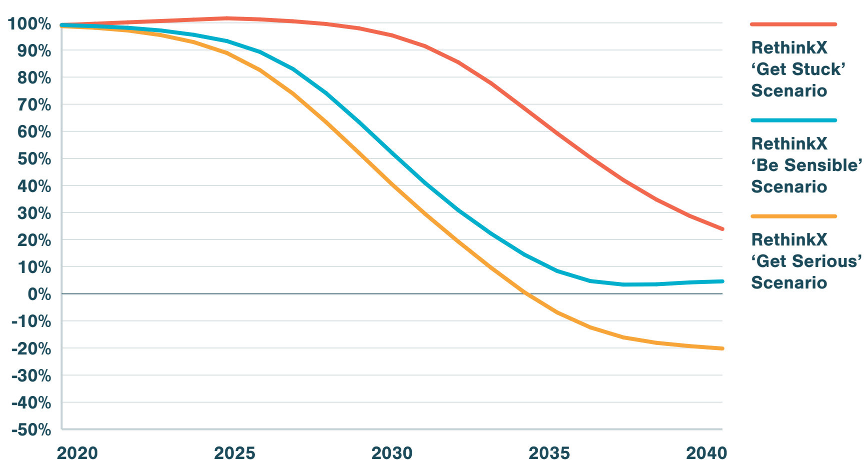
Figure 5: The RethinkX Delayed Disruption Scenario: 'Get Stuck'



Sources: IPCC, Our World in Data, Global Carbon Project, RethinkX.[12,13,14,15]

Figure 6 shows the three RethinkX scenarios together.

Figure 6: RethinkX Disruption Scenarios



Source: RethinkX.

Emissions Mitigation by Sector

Table 1 is based on data assembled by the Our World in Data project at Oxford University, and shows that the majority of global greenhouse gas emissions today (56.7%) are associated with energy use, primarily in the form of carbon dioxide (CO_2) produced from the burning of fossil fuels. Emissions from the food sector, largely in the form of methane (CH_4) and nitrous oxide (N_2O), comprise 18% of global emissions. The transportation sector comprises a smaller share at 16.2%, but the sub-sector of road transportation is the largest single source of emissions at 11.9%. Other sources outside these three sectors amount to 8.4% of global emissions, the largest source of which is cement production at 3%. These data show that over 90% of global emissions fall into the three sectors poised for disruption over the next 15 years.[13]

Table 1: Emissions by Sector and Sub-Sector

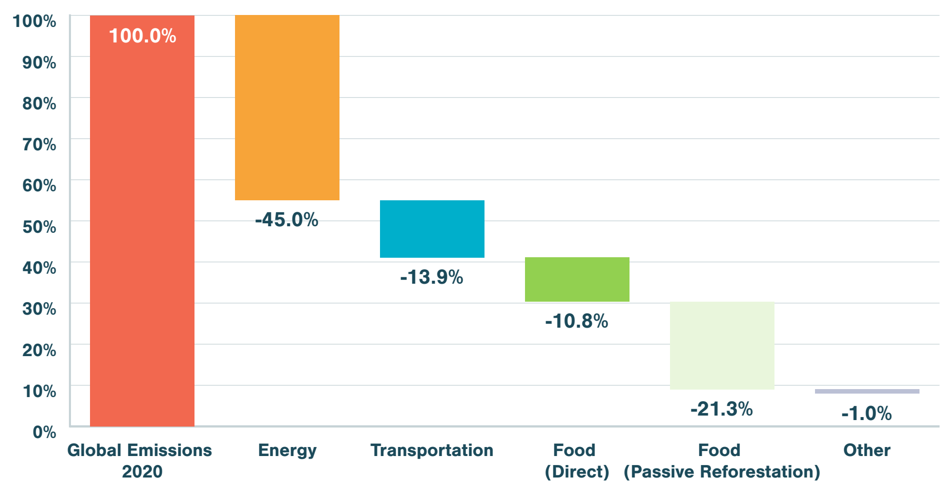
Sector	Sub-Sector	2020 Fraction of Global GHG Emissions (2016 baseline)
Energy	Residential Buildings	10.9%
	Other industry	10.5%
	Unallocated Fuel Combustion	7.8%
	Iron & Steel	7.1%
	Commercial Buildings	6.6%
	Fugitive Oil & Natural Gas	3.9%
	Chemical & petrochemical (energy)	3.5%
	Fugitive Coal	1.9%
	Energy in Agri & Fishing	1.7%
	Food & tobacco	1.0%
	Non-Ferrous metals	0.7%
	Paper and Pulp	0.6%
	Machinery	0.5%
	Sub-Total	**56.7%**
Transportation	Road Transportation	11.9%
	Aviation	1.9%
	Shipping	1.7%
	Rail	0.4%
	Pipeline	0.3%
	Sub-Total	**16.2%**
Food	Livestock & Manure	5.8%
	Agricultural Soils	4.1%
	Crop Burning	3.5%
	Deforestation	2.2%
	Cropland	1.4%
	Rice Cultivation	1.3%
	Grassland	0.1%
	Sub-Total	**18.0%**
Other	Cement	3.0%
	Chemical & petrochemical (industrial)	2.2%
	Landfills	1.9%
	Wastewater	1.3%
	Sub-Total	**8.4%**

Note: sub-sector percentages in Table 1 do not quite sum to 100% because these are numbers for 2020 relative to the dataset baseline year of 2016.

Sources: Our World in Data (baseline 2016), Global Carbon Project.[13,14,15]

Figure 7 shows that by 2035, in our 'Be Sensible' scenario, the SWB disruption of energy eliminates 45% of global emissions, the A-EVs and TaaS disruption of transportation eliminates 13.9% of global emissions, and the PFCA disruption of food eliminates 32.1% of global emissions. Importantly, the food disruption is able to eliminate more emissions than that sector currently comprises because the 2.7 billion hectares of land freed up from animal agriculture will naturally capture and store a large quantity of carbon through passive reforestation, even without any active reforestation efforts. The three sector disruptions together can therefore mitigate over 90% of greenhouse gas emissions worldwide within 15 years.

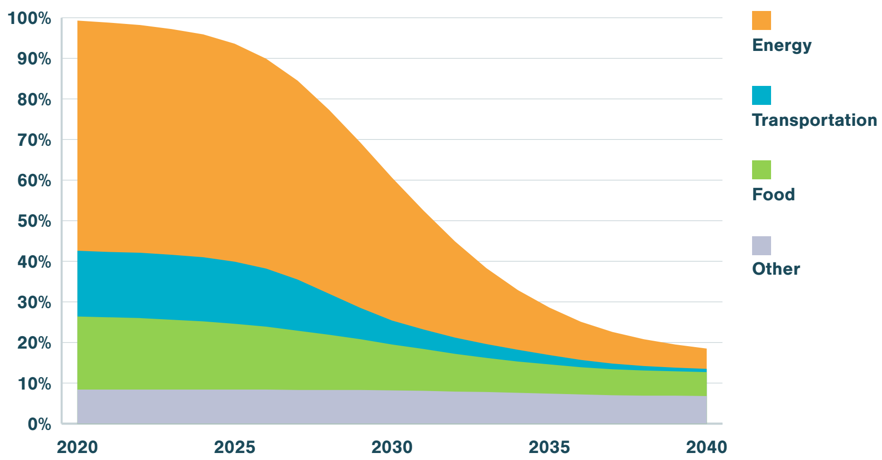
Figure 7: Emissions Mitigation and Offset by 2035 by Sector in the 'Be Sensible' Scenario



Source: RethinkX.

Figure 8 shows the direct emissions mitigation caused by the three sector disruptions in our 'Be Sensible' scenario, excluding carbon withdrawal from passive reforestation on the 2.7 billion hectares of land freed up by the food disruption. Energy emissions are reduced to a small fraction of their current amount. Transportation emissions are almost entirely eliminated, with only a small quantity remaining in difficult-to-electrify applications like long haul aviation and shipping. Food emissions are reduced by over half. Other sources of emissions such as cement production and landfills decline only slightly, as they are not directly affected by the three sector disruptions (see The Last Carbon Problem).

Figure 8: Emissions Mitigation by Sector in the 'Be Sensible' Scenario (excluding passive reforestation)



Note: sub-sector percentages in Table 1 do not quite sum to 100% because these are numbers for 2020 relative to the dataset baseline year of 2016.

Source: RethinkX.

Decarbonization Readiness – A Guide for Decision-Making

Each sub-sector of the global economy will be affected by the disruption of energy, transportation, and food differently. In some sub-sectors such as road transportation, decarbonization will run directly parallel to the disruption itself without lag because no additional technologies are required beyond SWB, A-EVs and TaaS, and PFCA driving the three disruptions. But in other sub-sectors, such as aviation, there is likely to be a lag in decarbonization because technological advancements in electric aircraft and energy storage are still required. Each sub-sector can therefore be categorized into one of three stages of mitigation readiness – 'Research', 'Deploy', or 'Scale'. The optimal choices and actions that investors, policymakers, civic leaders, and other decisionmakers must take differs at each readiness stage – as reflected in the names of the stages themselves. These choices and actions are summarized in general terms in Table 2.

Table 2: Choices and Actions by Decarbonization Readiness Stage – A Guide for Decision-Making

Decarbonization Readiness Stage	Choices and Actions
Research	» Technological potential to decarbonize the sub-sector has been identified, but substantial progress is still required to reach commercial viability » Government funding to support R&D » Private investment to support R&D
Deploy	» The technology needed to decarbonize the sub-sector has been validated and is ready for commercial deployment, but must be refined through experience in order to become competitive » Government policy is needed to design efficient markets with judicious use of regulations, standards, mandates, and prohibitions » Temporary government support and subsidies are appropriate for phase-in of the new technology » Longer term investment is needed to finance initial deployment
Scale	» The technology needed to decarbonize the sub-sector is proven and ready to scale » Government policy is required to remove market barriers, break up existing monopolies, guarantee rights to produce and trade using the new technology, and end existing protections for incumbent industries based on older technologies » Public and private investment can finance deployment

Source: RethinkX.

The decarbonization readiness stages correspond to the maturity of the technologies required to mitigate emissions from that sub-sector. These technologies include not just SWB, A-EVs and TaaS, and PFCA, but any other additional technologies required for decarbonization.

For example, virtually all emissions from fugitive oil and gas will be directly eliminated by the energy and transportation disruptions without requiring additional technologies, so we categorize this sub-sector as ready to Scale because the technologies required for decarbonization – SWB, A-EVs, and TaaS – are already being deployed to market.

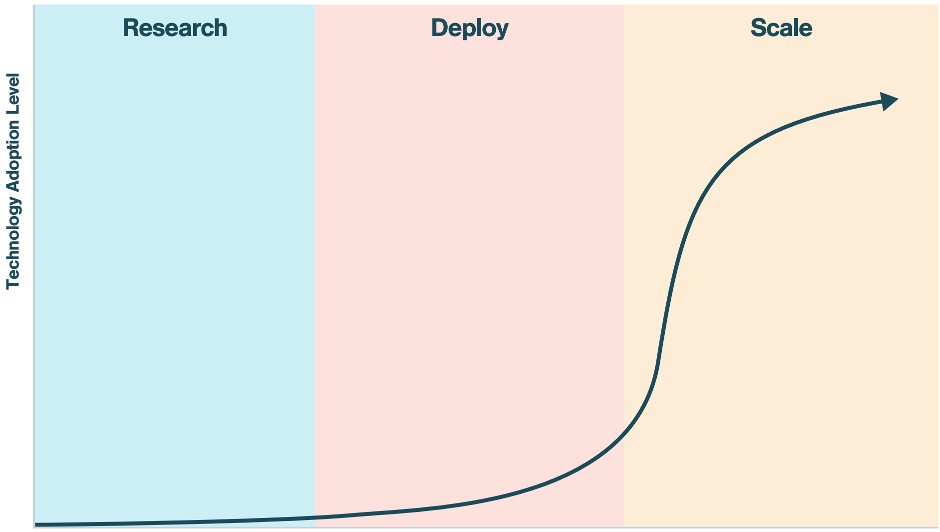
For the example of residential heating, we categorize the sub-sector in the Deploy stage because it not only requires SWB to supply clean energy, but also needs additional technologies such as induction cooktops to replace gas stoves, electric water heaters to replace gas water heaters, and electric heat pumps to replace gas furnaces and oil-fired boilers. Similarly, the decarbonization of the iron and steel sub-sector in addition to SWB requires electrification of the industrial heating processes and alternatives to carbon from coke as reducing agents. No further research is required to apply these additional technologies, but they would benefit greatly from the choices and actions described in Table 2 to help deploy them to market.

Finally, we categorize sub-sectors such as wastewater or rice cultivation as being at the Research stage because there are few if any technologies currently on the horizon that would allow them to achieve full decarbonization, meaning support for further R&D is required.

Categorizing sub-sector sources of emissions according to their decarbonization readiness offers a powerful guide for decision-making based on how to prioritize our efforts to maximize emissions reduction as soon as possible. Without such a framework, decisionmakers are left with a 'whack-a-mole' approach rather than a focused approach to fighting climate change, which runs the risk of misallocating financial, material, and political resources. Furthermore, this guide shows where economic, social, and environmental incentives and goals can be realigned by clean technologies, and therefore where the power and efficiency of market forces can be leveraged to drive emissions mitigation instead of relying solely on governments to do the heavy lifting.

Figure 9 shows that the stages of readiness tend to correspond to phases of the relevant technologies' adoption S-curves.

Figure 9: Stages of Decarbonization Readiness



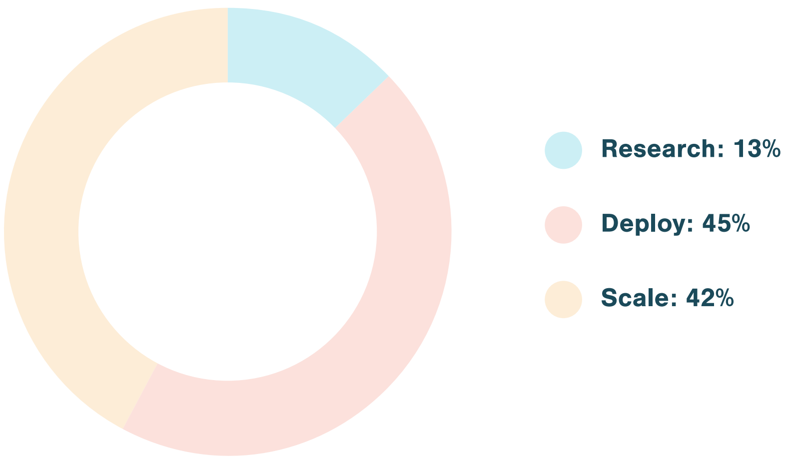
Source: RethinkX.

A key implication of this analysis is that 87% of global emissions today come from sub-sectors that are in either the Scale or the Deploy stage, and so mitigation of these emissions can therefore be driven largely by market forces.

The right choices and actions are required for governments, investors, and other decisionmakers to help graduate sub-sectors from the Deploy stage into the Scale stage, and to ensure that scaling proceeds as quickly as possible. Only 13% of global emissions currently come from sub-sectors for which more R&D is still required before the technologies needed to decarbonize them are commercially viable.

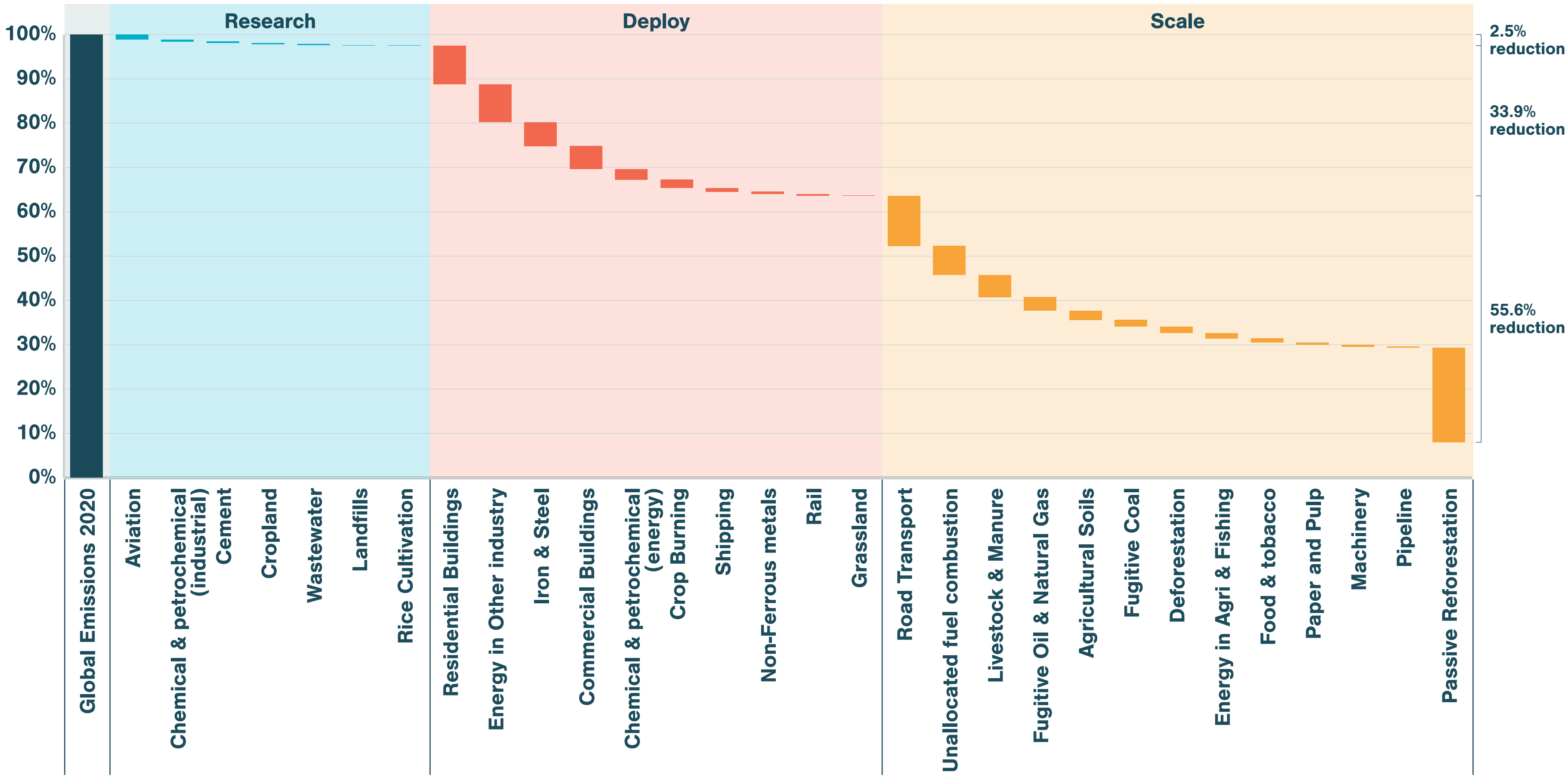
Figure 10 and Figure 11 show that the overwhelming majority of emissions reductions that are achievable over the next 15 years in our 'Be Sensible' scenario come from sub-sectors that are either ready to be decarbonized directly by scaling SWB, A-EVs and TaaS, and PFCA, or that are ready to be deployed to market and can quickly graduate to the Scale stage if supported by the right choices and actions from governments, investors, and other decisionmakers.

Figure 10: Share of Global Emissions by Decarbonization Readiness Stage



Sources: Our World in Data (baseline 2016), Global Carbon Project, Andrews et al., 2018.[13,14,16]

Figure 11: Emissions Reductions by 2035 by Decarbonization Readiness Stage in the 'Be Sensible' Scenario



Source: RethinkX.

The Last Carbon Problem

For some sources of emissions in several sub-sectors (namely chemical & petrochemical industry, cement, cropland, wastewater, rice cultivation, crop burning, agricultural soils, and fugitive coal) it will not be possible to decarbonize entirely with any existing or foreseeable technologies. Solutions to this 'Last Carbon Problem' fall into three categories: 1) limit consumption in these niche markets; 2) decarbonize these niche markets; or 3) offset the emissions of these niche markets. Conventional analyses overestimate the scale of the Last Carbon Problem and underestimate the potential of technology to solve it, leading them to focus on solutions in the first category.

Fortunately, the Last Carbon Problem is smaller and therefore more manageable than conventional analyses assume. Only 10% of 2020 emissions remain by 2035 in our 'Be Sensible' scenario. Researching technologies for decarbonizing these niche markets is of course possible, but in many cases it is unlikely to be the most cost-effective option. Instead, the disruptions of energy, transportation, and food themselves will make carbon withdrawal far more affordable and feasible by lowering the cost of clean energy and machinery, and by making extremely large quantities of land available for active reforestation (see Box 3: Going Below Zero Emissions).

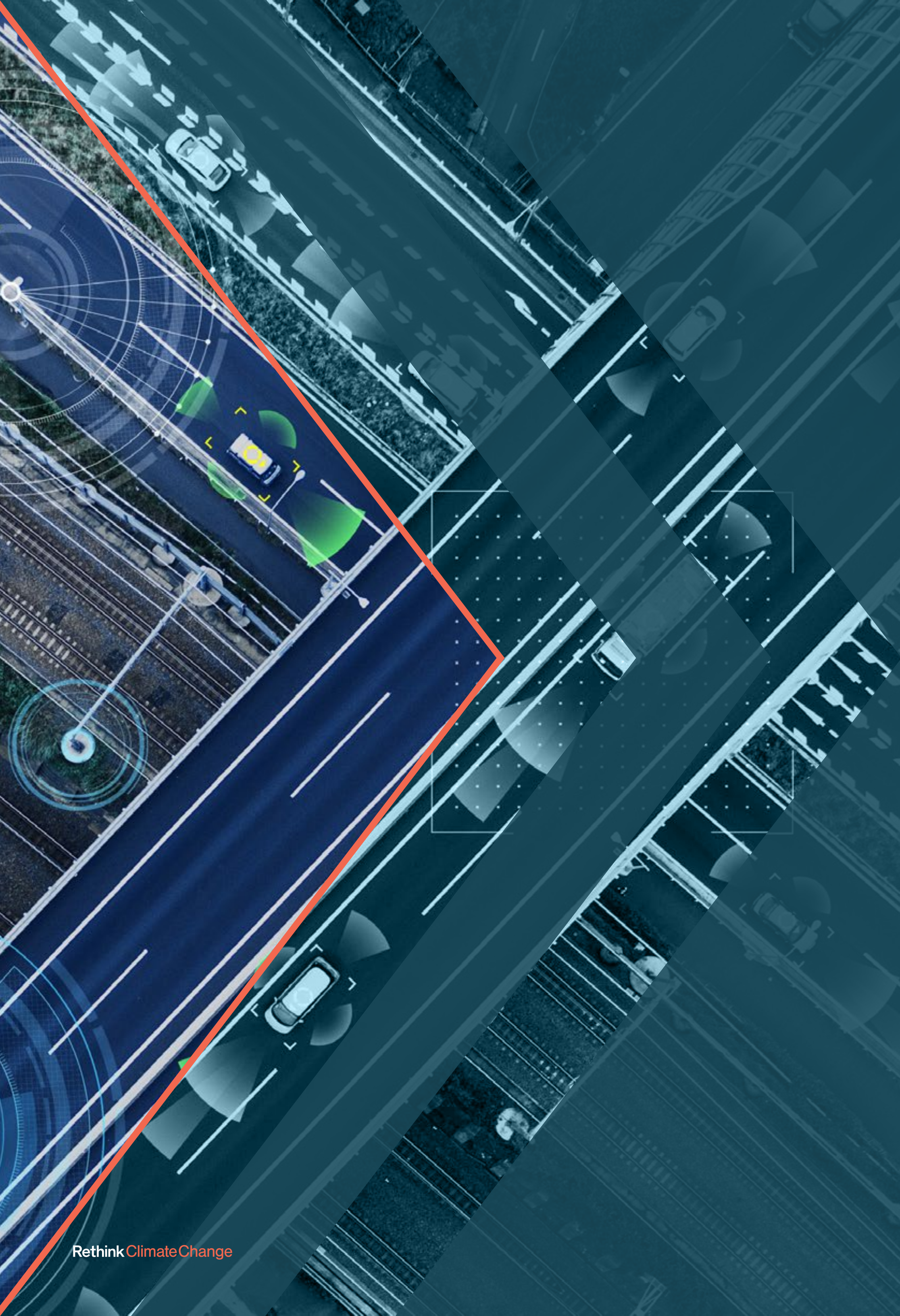
Box 3: Going Below Zero Emissions

Achieving net zero emissions is only the first step to solving climate change. We must also return the atmospheric concentration of carbon dioxide to a safe level because the long residence time of CO_2 in the atmosphere means that past emissions will continue to drive global warming for centuries unless we take action to remove it. Even if we manage to keep atmospheric carbon to 450ppm, current research indicates that there is only a 66% likelihood this will limit mean global temperature rise to less than 2°C above baseline and avert the worst impacts of climate change.[d] These are terrible odds for such a consequential risk, and so it will also be necessary to withdraw large quantities of carbon from the atmosphere to ensure that we avoid disaster.

By analogy, humanity is like a child in a bathtub that has begun to overflow. The first step to stopping the overflow is to turn off the tap. The second is to drain the bathtub back down to a level safe for the child. Just as turning off a tap cannot drain a bathtub, merely mitigating the flow of new emissions cannot reduce the existing stock of carbon dioxide already in the atmosphere. And it is too dangerous to wait for the water to evaporate naturally. Following this analogy, climate change cannot ultimately be solved through individual or collective austerity, because reducing consumption (turning off the tap) does not withdraw any carbon from the atmosphere.

As there is currently no clear scientific consensus on how much carbon withdrawal will be necessary to avoid the worst impacts of climate change, the most sensible precautionary approach is to fully restore the atmosphere to its pre-industrial composition. This requires the removal of hundreds of gigatons of carbon. Although this seems an overwhelming challenge, the very same technologies disrupting energy, transportation, and food will make restoring the atmosphere through carbon withdrawal technologically and economically feasible for the first time.

Clean, cheap energy and productivity from A-EVs and other machine labor will dramatically reduce the cost of both active reforestation as well as technology-based approaches to carbon withdrawal such as ocean alkalinity enhancement (OAE) and direct air carbon capture and storage (DACCS). Meanwhile, the 2.7 billion hectares of land free up from animal agriculture by the food disruption – equivalent to the combined size of the United States, China, and Australia – is nearly three times higher than the 1 billion hectares of land that the UN Environment Programme recommends be restored to keep global average temperatures below 2°C temperature rise.[17] We estimate that the disruptions of energy, transportation, and food will together reduce the cost of carbon withdrawal to under $10 per ton by 2040.



Part 2:

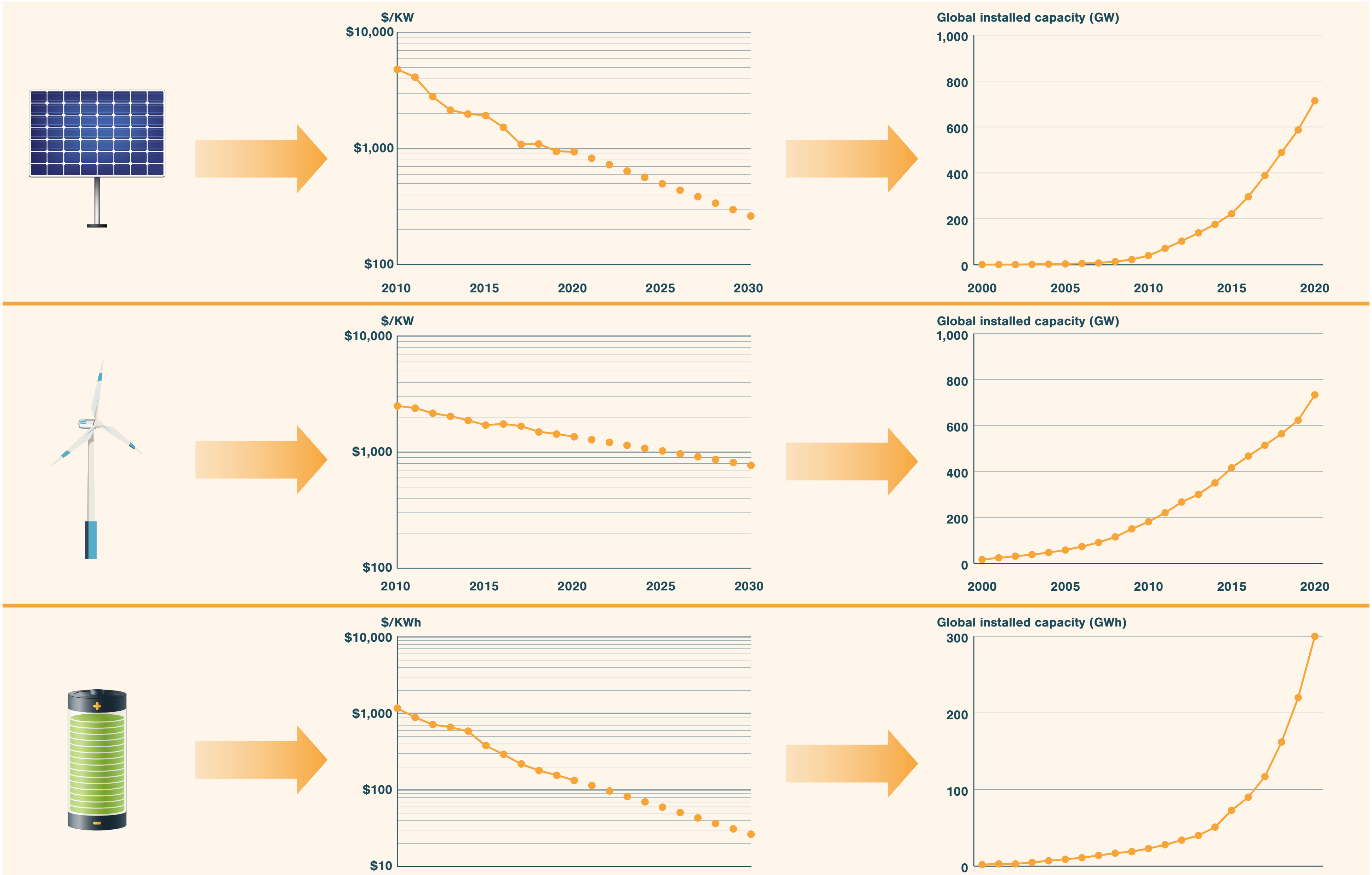
The Disruption of Energy, Transportation, and Food

Our three scenarios are based on the predictable trajectories of disruption in the energy, transportation, and food sectors.

For over a decade, the RethinkX team has accurately predicted the dramatic cost improvements and market growth of SWB in the energy sector, A-EVs and TaaS in the transportation sector, and PF in the food sector. The approach RethinkX uses, which is based on the Seba Technology Disruption Framework and empirically validated against dozens of historical disruptions since the 19th Century, provides a powerful lens through which to view the full complexity of technology disruptions. (See Appendix B for additional information).

Disruption of the Energy Sector

Figure 12: The Disruption of Energy



Source: RethinkX.[4]

The disruption of the energy sector will be driven by the economics of solar photovoltaics, onshore wind power, and lithium-ion batteries (SWB), which already outcompetes conventional power generation and will displace fossil fuels and conventional nuclear power during the 2020s.[4] The costs and capabilities of each of these technologies have been consistently improving for several decades (see Appendix B). Since 2010 alone, solar PV capacity costs have fallen over 80%, onshore wind capacity costs have fallen more than 45%, and lithium-ion battery capacity costs have fallen almost 90%.[18,19,20,21] These cost improvements are consistent and predictable, and each of the technologies will continue to traverse its remarkable experience curve throughout the 2020s.

Incumbent coal, gas, and nuclear power plants are already unable to compete with new solar and wind installations for generating capacity.[7] By 2030, they will be unable to compete with battery-firmed capacity that makes electricity from solar and wind available all day, all night, all year round. This means that the disruption of conventional energy technologies is now inevitable.

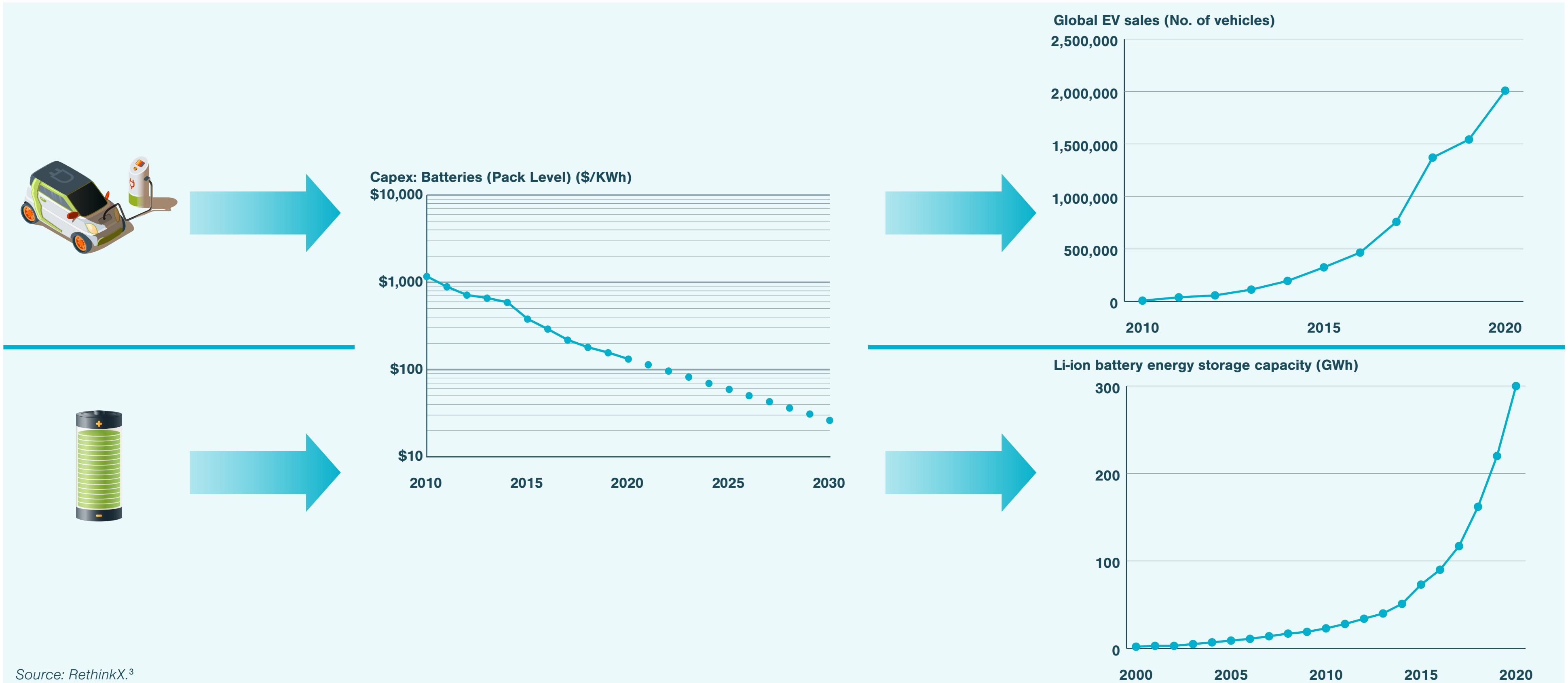
Policymakers, investors, civic leaders, and the general public are under the false impression that solar PV and wind power cannot supply 100% of electricity without weeks' worth of battery energy storage. This is because conventional models fail to understand that future solar and wind generating capacity will greatly exceed the total electricity generating capacity installed today. Our research reveals a fundamental tradeoff relationship between generation capacity and energy storage capacity which we call the *Clean Energy U-Curve*. When costs are optimized correctly between the two, 100% SWB systems are not only achievable but are by far the cheapest available option out to 2030 both for new power provision and in many cases compared to existing conventional power plants.

As SWB adoption accelerates, these technologies will produce an increasingly large surplus of energy at near-zero marginal cost that we call *Clean Energy Super Power (or super power)*. Because the SWB system's capacities must be designed to fully meet electricity demand during the most challenging times of year such as the cloudy weeks of winter when the days are shortest, they are able to produce much more power throughout the rest of the year. Just as we saw with the Internet and the demand response to information and communication at near-zero marginal cost, the resulting superabundance of clean energy will open the door to extraordinary new possibilities for society, the economy, and the environment. Paired with electrification, super power will be able to supply clean energy for a wide range of previously carbon-intensive services such as water desalination and filtration, road transportation, residential and commercial heating, waste management, and industrial and chemical processes.

Unlike fossil fuels, nuclear power, or even hydropower, the ability to deploy solar PV and batteries virtually anywhere at any scale will lead to the localization, decentralization, and democratization of energy production. This new more stable and resilient energy production system will allow less developed countries and communities to close poverty and equity gaps by leapfrogging over previous barriers to human development.

Disruption of the Transportation Sector

Figure 13: The Disruption of Transportation



Source: RethinkX.[3]

Our previous research has shown that the transportation disruption will unfold in two phases. In the first phase, EVs will displace internal combustion engine (ICE) vehicles driven by rapid cost reductions. By the late 2020s, this disruption will cause all new vehicles produced to be electric, as powerful feedback loops force ICE vehicle manufacturing to collapse. However, this first phase will itself be overtaken by a second phase of disruption driven by the economics of autonomous electric vehicles (A-EVs) providing transportation-as-a-service (TaaS). In the late 2020s, ICE and private vehicle ownership will be replaced by on-demand A-EVs owned by TaaS fleets, not individuals. As with other disruptions, the costs and capabilities of each of these technologies have been consistently improving for several decades and will be the primary driver of the transportation disruption for passenger and freight vehicles alike.

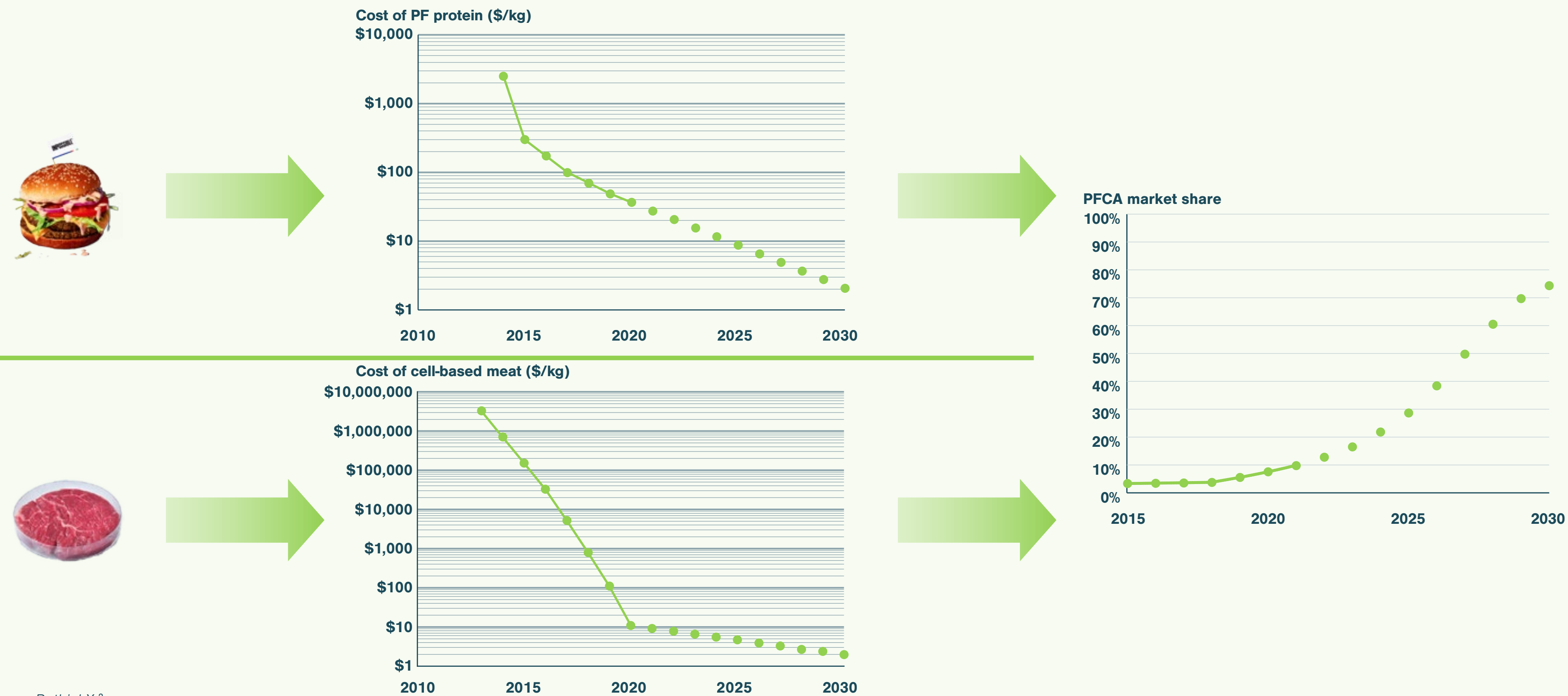
The operating cost of EVs is already lower than ICE vehicles, and their initial costs are also rapidly approaching parity. Because electric drivetrains can last over a million miles (seven times longer than an ICEV) in high utilization models (freight and ride-hailing) where vehicles are in service most of the day, the cost per mile of transport will plunge as the cost of the vehicle is spread over a vastly lengthened lifetime. Even without autonomous technology, EVs are on track to make on-demand transportation cheaper than ICE-based models, expanding this market. Once available, autonomous technology will remove the labor cost of ride service, leading to a cost-per-mile for TaaS ten times cheaper than privately-owned vehicles today and leading to a rapid disruption.

As the utility of old vehicles relying on fossil fuels and a human driver rapidly approaches zero, most people will stop owning vehicles altogether, instead accessing them when needed, having goods delivered autonomously, and travelling with smaller vehicles when convenient – dramatically reducing the number of cars on the road. Ride hailing services such as Uber and Lyft give a preview of the impact that TaaS will have. Private vehicle ownership will cease to be the prevailing road transportation model, with new car sales and the existing fleet being displaced by EVs and later A-EVs as car owners switch to TaaS.

Beyond road transportation, short haul aviation (which comprises about one third of emissions from commercial aviation) will be disrupted by the combination of electric aircraft and overnight road trips in A-EVs.[22] Emissions from shipping will also be disrupted by a combination of electrification of ships along with changes in commodity demand: the largest categories of freight including crude oil, oil products, coal, natural gas, iron ore, steel, automobiles, grain, and livestock will all see demand plummet as a result of the three disruptions (see Box 5: Cascading Effects of Disruption Lead to Big Surprises).

Disruption of the Food Sector

Figure 14: The Disruption of Food



Source: RethinkX.[2]

The food disruption will be driven by the economics of precision fermentation (PF) and cellular agriculture (CA), which will compete with animal products of all kinds. Our previous research found that PF will make protein production 5 times cheaper by 2030 and 10 times cheaper by 2035 than existing animal proteins. The precision with which proteins and other complex organic molecules will be produced also means that foods made with them will be higher quality, safer, more consistent, and available in a far wider variety than the animal-derived products they replace. The impact of this disruption on industrial animal farming will be profound.

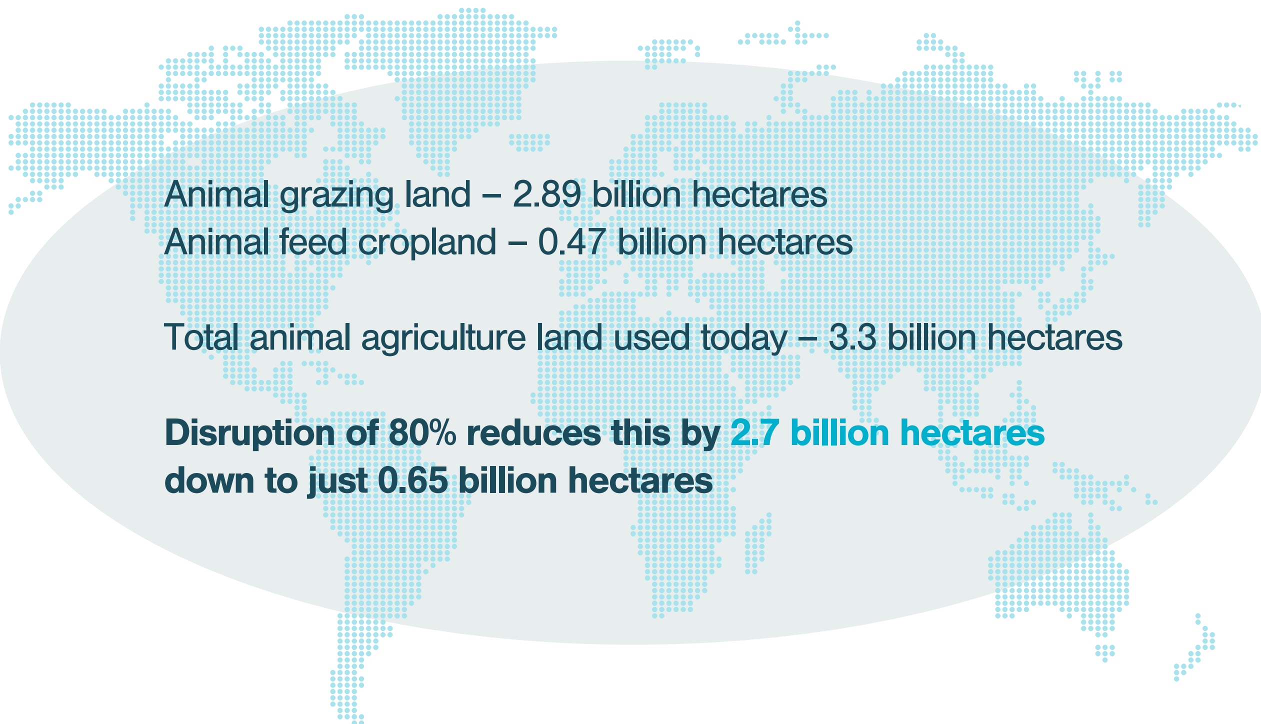
The economic competitiveness of foods made with PF technology will be overwhelming. As the most inefficient and economically vulnerable part of the industrial food system, cow products will be the first to feel the full force of the food disruption. New PF foods will be up to 100 times more land efficient, 10-25 times more feedstock efficient, 20 times more time efficient, and 10 times more water efficient. They will also produce far less waste. By 2030, the number of cows in the United States will have fallen by 50% and the cattle farming industry will be all but bankrupt. All other commercial livestock industries worldwide will quickly follow the same fate, as will commercial fisheries and aquaculture.

The disruption of the ground meat market has already begun, and adoption will tip and accelerate exponentially once cost parity is reached. But it will not rely solely on the direct, one-for-one substitution of end products. In some markets, only a small percentage of ingredients need to be replaced for an entire product to be disrupted. The whole of the cow milk industry, for example, will begin to collapse once PF technologies replace the proteins in a bottle of milk – just 3.3% of its content. Product after product that we extract from animals will be replaced by superior, cheaper, cleaner, and tastier alternatives, triggering a death spiral of increasing prices, decreasing demand, and reversing economies of scale for the livestock and seafood industries.

A new production model called Food-as-Software is emerging alongside PFCA, in which individual molecules engineered by scientists are uploaded to databases – molecular cookbooks that food engineers anywhere in the world can use to design products in the same way software developers design apps. This model ensures constant iteration so that products improve rapidly, with each version superior and cheaper than the last. It also means that the PFCA food system will be decentralized and therefore much more stable and resilient than industrial animal agriculture, with fermentation farms located in or close to towns and cities just as breweries are today.

Today, animal agriculture consumes 3.3 billion hectares of land in the form of pasture and feed cropland.[23] The food disruption will free up 80% of that land – an area the size of the United States, China, and Australia combined. This staggering transformation will present an entirely unprecedented opportunity for conservation, rewilding, and reforestation. Even without active reforestation, the passive reforestation of this land through the process of natural recovery will capture and store a quantity of carbon equivalent to up to 20% of today's global emissions (see Appendix C for details).[e]

Figure 15: Land Area Freed from Animal Agriculture by the Food Disruption by 2040



For comparison:

United States land area – 0.93 billion hectares
China land area – 0.91 billion hectares
Australia land area – 0.76 billion hectares

Total of all three – **2.6 billion hectares**

Freed land by 2040 = area of US, China, and Australia combined

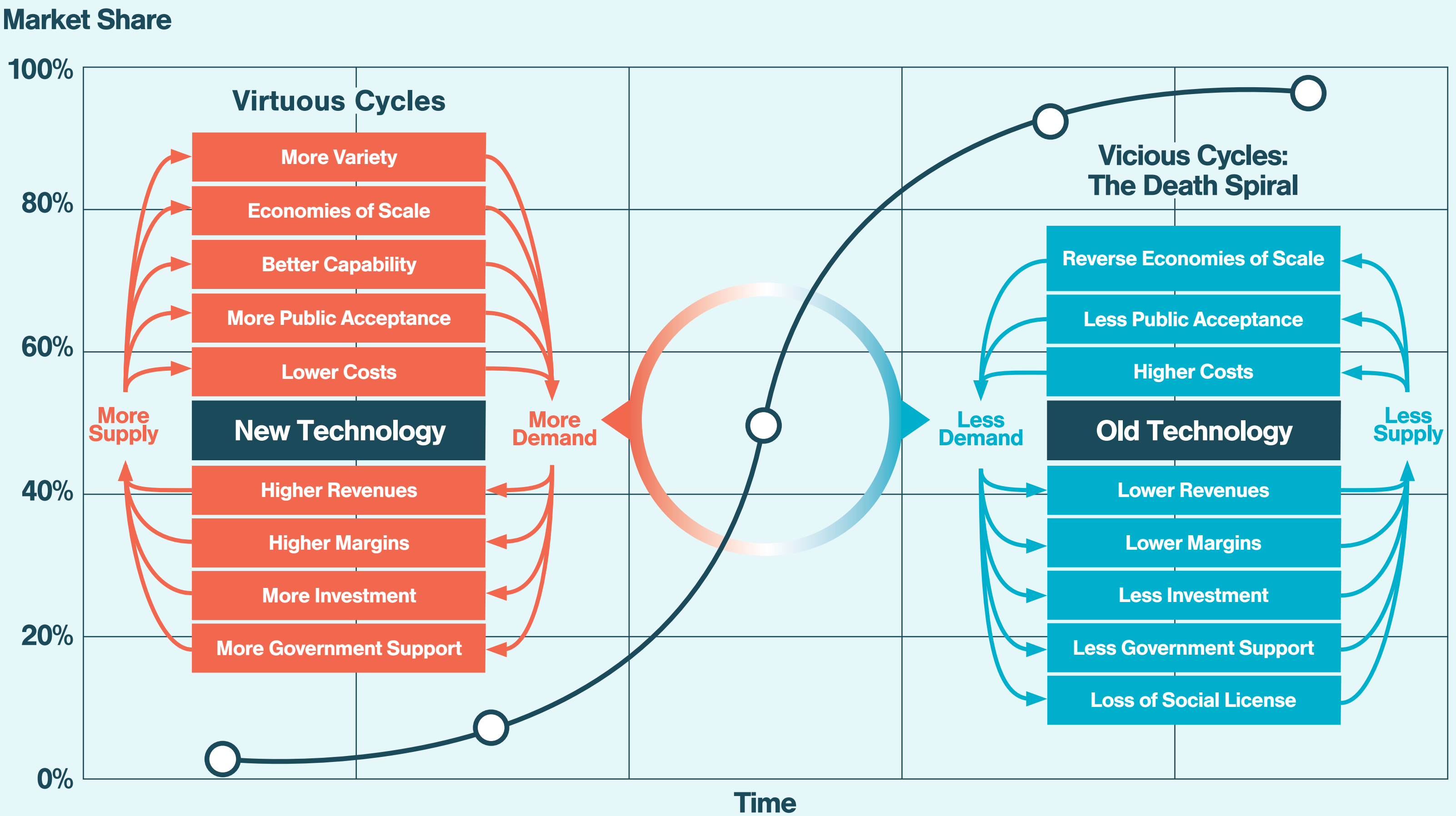
Source: RethinkX, Hayek et al., 2020.[23]

The food disruption will also end commercial fisheries and aquaculture which already operate on very thin margins and will be unable to compete with superior alternatives at a substantially lower cost. The food disruption will therefore initiate an unprecedented recovery of marine ecosystems. Although the quantity of carbon stored in marine biomass is relatively small compared to its terrestrial counterparts, there will nevertheless be climate change and other ecological benefits from the healing of the world's oceans as well.[24]

Box 4: The Surprising Speed of Disruption

Disruptions are driven by the convergence of new technologies that trigger causal feedback loops within and across markets and sectors. History shows that these loops interact with and amplify one another, accelerating the adoption of new technology in a virtuous cycle while accelerating the abandonment of old technology in a vicious cycle. The net result of these systems dynamics is that disruption tends to unfold with surprising speed. We see this same basic pattern repeat with technologies and industries of all kinds.

Figure 16: Causal Feedback Loops Drive Disruption

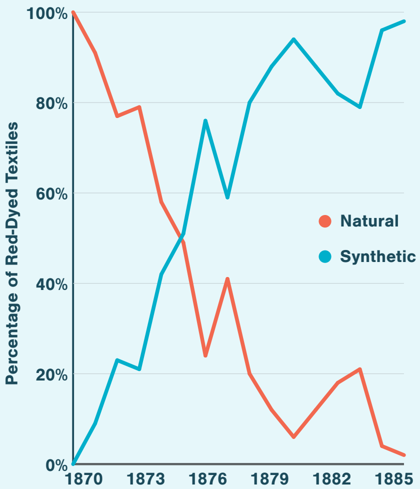


Source: RethinkX.

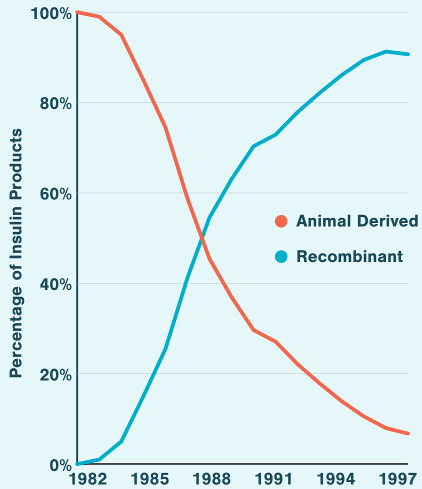
We already see indications that incumbent industries in the energy, transportation, and food sector have entered their disruption death spirals because they have begun to lose their social license. For example, many governments have now committed to phasing out fossil fuel use in the energy and transportation sectors, and shareholders are demanding change as the value of firms like ExxonMobil, Chevron, BP, and Shell has begun to erode.[25,26,27,28]

X Marks Disruption – Historical Examples

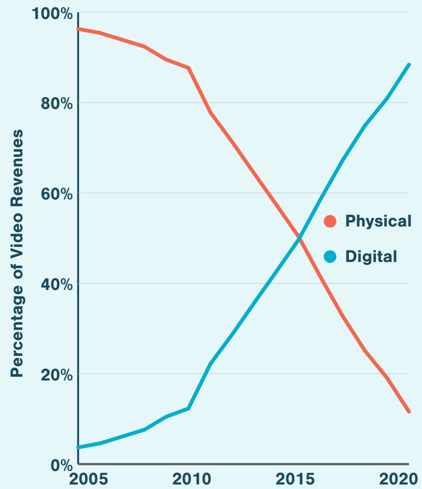
Red Fabric Dyes



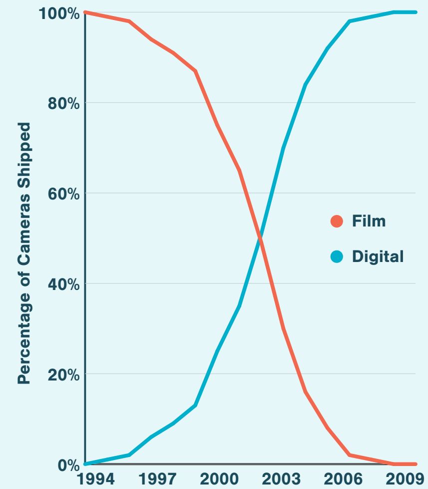
Insulin



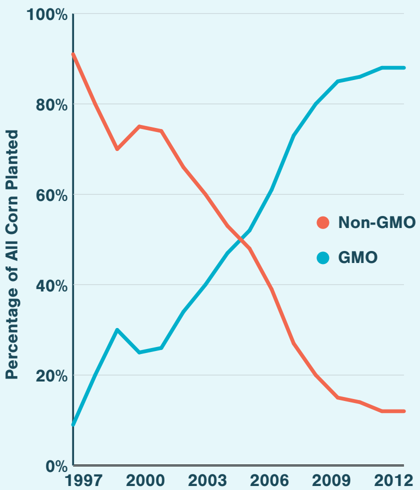
Video



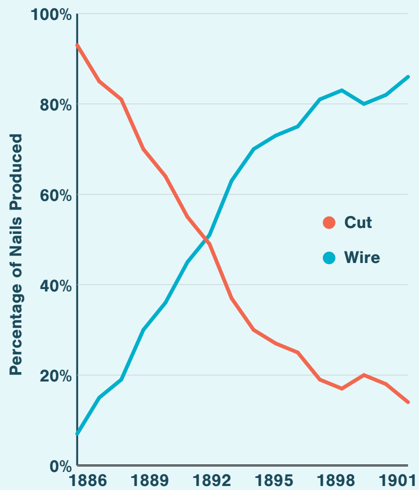
Cameras



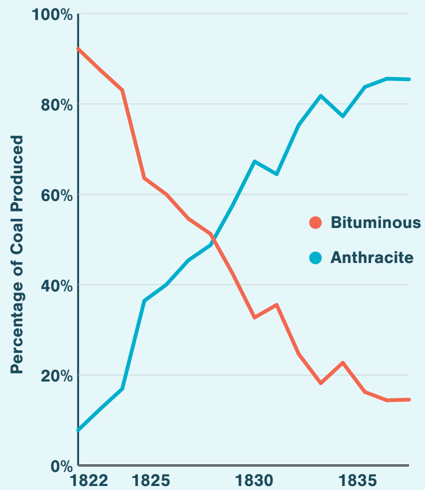
Corn



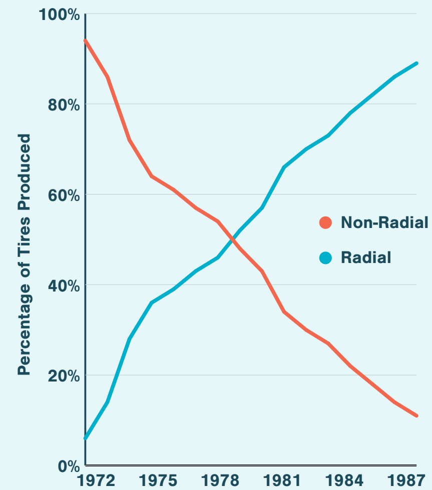
Nails



Coal



Car Tires



Source: RethinkX, Lopez, 1989., IMS Health, DEG, Widescreen Review, CIPA, USDA, Adams, 2002., NBER, U.S. Census Bureau, Rajan et al., 2000.[29,30,31,32,33,34,35,36,37,38]

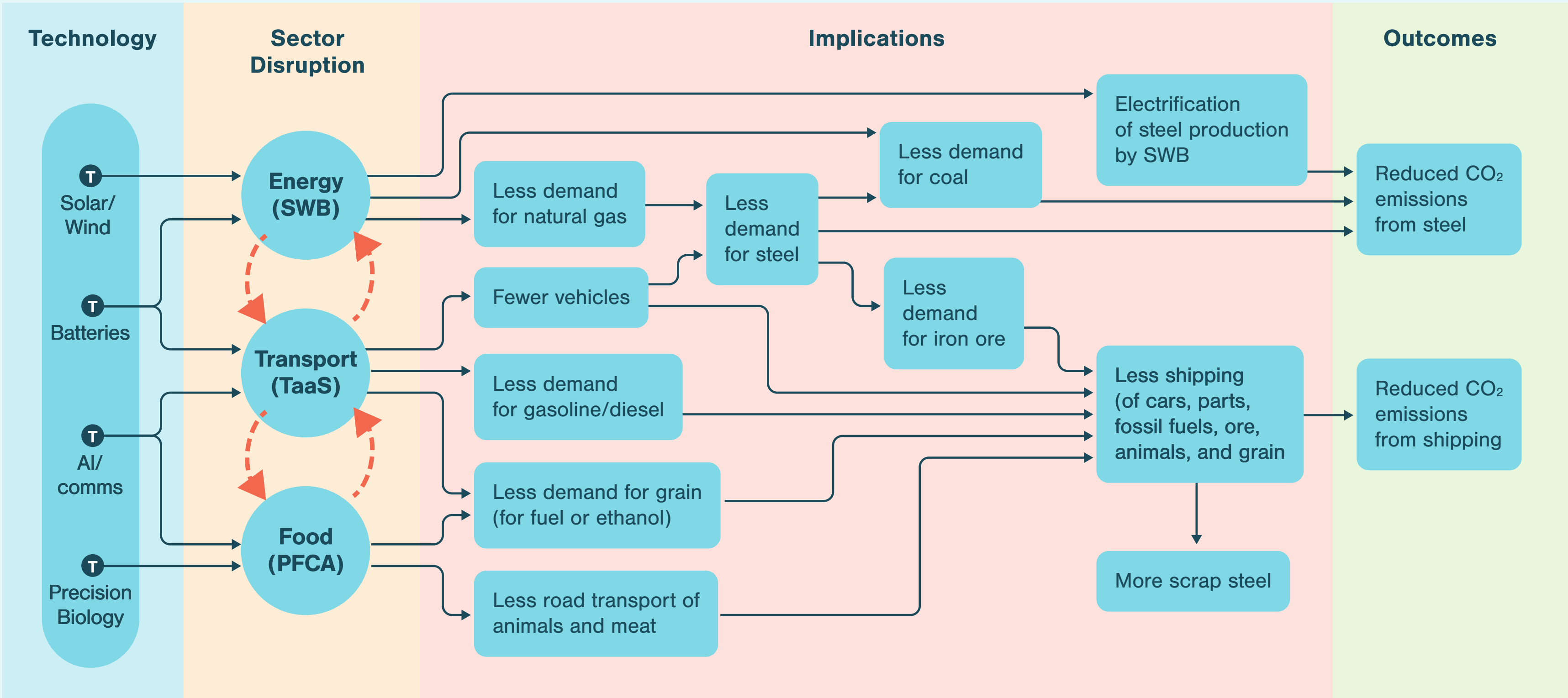
Simultaneous Disruptions and Technology Convergence

Because they are foundational sectors, the disruption of energy, transportation, and food will have cascading second and third order effects across all other sectors of the global economy, generating a host of extraordinary emergent benefits and opportunities across sectors for further emissions reductions and environmental restoration. Like other technology disruptions throughout history, these technologies are not merely a one-to-one replacement of existing technologies, but offer additional capabilities and properties with wholly new uses. The automobile, for example, did not simply substitute for horses. Their vastly greater capability and diversity created entirely new markets based on novel business models that served previously unmet needs – generating trillions of dollars in additional value as a result. Electricity, the Internet, personal computers, and smartphones offer similar examples of how the disproportionality of disruption creates new systems with emergent properties, with both unexpected benefits as well as unexpected detriments (like greenhouse gas emissions).

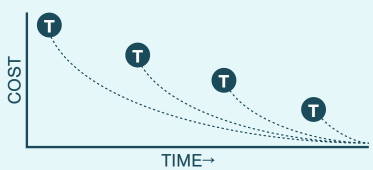
Virtually every sub-sector of the economy will therefore be directly or indirectly impacted. In many cases, these impacts are not merely additive but are complex, unintuitive, and multiplicative. In the case of road transportation, for example, emissions will be mitigated not only by the electrification of vehicles, but also by the decarbonization of electricity itself due to the energy disruption, and the elimination of a significant fraction of vehicle miles travelled for transportation of livestock, grain, and animal products rendered obsolete by the food disruption. As the transportation disruption dramatically reduces the number of vehicles on the road, this will also reduce the demand for materials like nickel for use in batteries from the transportation sector. A similar account can be given for each of the other 28 sub-sectors.

Box 5: Cascading Effects of Disruption Lead to Big Surprises

Figure 17: Cascading Effects of Disruptions on Iron and Steel



1st Order Disruption



Improvements in cost and capability of different technologies drives convergence; enabling new products, services and business models which disrupt existing markets and create new possibilities.

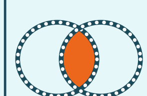
2nd Order Disruption

Tech Disruption

Disruption within one sector impacts cost and capabilities of underlying technologies. For example, improvements to batteries in electronics drives the EV disruption, which in turn drives the accelerating disruption of electric power.

Feedback Loops

Cross Sector Disruption



Disruption to one sector creates new possibilities in other sectors. For example, disruption to information and communications impacts the need to travel for work, education, entertainment, retail, and so on.

Cascading Impacts

The impacts of disruption cascade across society. For example, disruption to transportation impacts geopolitics, greenhouse gas emissions, the layout of cities and participation in economy.

Source: RethinkX.

The cross-sector ripple effects and cascading impacts of disruptions means that they produce surprising and counterintuitive outcomes. The example of the steel industry provides a good illustration of this phenomenon in relation to GHG emissions and climate change.

The steel industry accounts for over 7% of global emissions, and is widely regarded as one of the most difficult sectors of the economy to decarbonize.[39,40] This is because the production of virgin steel requires a large amount of energy to melt iron ore, and also creates carbon dioxide by using carbon to remove oxygen from the iron ore. But the energy, transportation, and food disruptions will do much more than just decarbonize the energy that steel production requires – they will also significantly reduce overall demand for virgin steel and create an enormous glut of scrap steel for reuse.

The demand for steel (as well as many other materials such as copper and nickel) in oil rigs, oil pipelines, and natural gas pipelines will simply disappear. Approximately 30% of all ship tonnage in the world is oil tankers, while about 40% consists of dry bulk cargo ships that carry coal, iron ore, cars, trucks, livestock, and grains.[41] As demand for these products and for the ships that transport them plummets, the world's fleet of cargo ships will shrink significantly, removing another source of steel demand while simultaneously creating the glut of scrap steel. Simultaneously, the world's fleet of over 4.5 million commercial fishing vessels will be wiped out by the food disruption, further reducing steel demand for new ships and adding to the scrap steel glut.[42]

Similarly, fossil fuels, livestock, grain for animal feed, and cars themselves are major sources of demand for ground transportation. In the United States, coal alone accounts for 20% of all ton-miles of goods transported.[43] This demand will fall drastically as the three disruptions unfold. The transportation disruption itself will reduce the number of cars and trucks on the road in 2030 compared to 2020 as we shift to A-EVs and TaaS. Without engines, the electric vehicles that remain will contain less steel than their internal combustion predecessors. Meanwhile, the use-value of the global fleet of gasoline and diesel vehicles that cannot drive themselves will plummet toward zero, sending the overwhelming majority of them to the scrapyard, contributing further to the glut of used steel, aluminum, copper, and other materials.

Steel is nearly 100% recyclable. Huge quantities of defunct ships, oil rigs and refineries, pipelines, cars, and trucks will provide an enormous stockpile of recyclable scrap steel, along with other metals. This scrap steel will be more than sufficient to supply the increase in demand for steel for the new industries such as solar PV and wind power installations in the energy sector and bioreactors in the food sector.

As the energy, transportation, and food disruptions move us closer toward the goal of decarbonizing steel production and recycling, they simultaneously shift the goalposts themselves closer to us by reducing demand.

Part 3:

Implications for Greenhouse Gas Emissions and Climate Change

The implications of the energy, transportation, and food sector disruptions for climate change are extraordinary. With just these three disruptions, we can eliminate 90% of net greenhouse gas (GHG) emissions worldwide by 2035. Market forces can be leveraged to do the bulk of the deployment and scaling work because the technologies required are either already commercially available and competitive today, or can reach the market before 2025 with the right societal choices. For the remaining 10%, the three disruptions will also make active reforestation and technology-based carbon withdrawal technically feasible and economically affordable for the first time.

Key Implications

1. We can achieve net zero emissions much more quickly than is widely imagined by deploying and scaling the technology we already have

Our analysis shows that the clean technologies driving the disruptions of the energy, transportation, and food sectors worldwide can cut global greenhouse gas emissions 90% by 2035. This is because the technologies we need to drive these disruptions already exist today and are either ready to deploy to market, or are already deployed and can scale immediately. As we already have the technologies we need to solve the climate crisis, we do not need fusion power or other major unproven breakthroughs to achieve net zero emissions. We only need to deploy and scale solar photovoltaics, wind power, and batteries (SWB), electric (EVs) and autonomous vehicles (A-EVs) providing Transportation-as-a-Service (TaaS), and precision fermentation and cellular agriculture (PFCA), as quickly as possible (see Box 4: The Surprising Speed of Disruption).

2. We can achieve net zero emissions without collateral damage to society or the economy

Our previous research has shown that SWB, A-EVs, TaaS, and PF are inherently superior to the incumbents. These clean new technologies will therefore rapidly outcompete and disrupt the older, dirtier industries through market forces alone. This means we are not dependent upon governments to impose draconian restrictions on either the supply or the demand side of the economy, which in turn means we can avoid the social harms of austerity policies that reduce standards of living and impede human development (the burden of which falls disproportionately on those communities and nations that are already disadvantaged). Indeed, economic contraction would only slow down the disruptions of the energy, transportation, and food sectors, and delay the achievement of net zero emissions. Governments, companies, organizations, and individuals who wish to reduce emissions should therefore focus on accelerating the adoption of SWB, A-EVs, TaaS, and PFCA rather than on austerity (see Box 2: Mistakes of Conventional Forecasting).

3. Markets can and must play the dominant role in reducing emissions

Our analysis shows that 42% of emissions can be eliminated by technologies that are ready to scale immediately, and a further 45% of emissions can be eliminated by already existing technologies requiring only modest additional refinement to be deployed, become cost-competitive, and start scaling before 2025. This means we can immediately harness the power of market forces to mitigate 87% of emissions worldwide. Because well-functioning markets align incentives, optimize resource allocation, and reward efficiency, we can harness their economic benefits and save trillions of dollars that would otherwise be lost to misguided investment in older technologies, while reducing the social and environmental costs of incumbent industries. It follows that a key role of government must be to enable well-functioning markets by removing barriers to the adoption of SWB, A-EVs, TaaS, and PF such as utility monopolies and livestock subsidies, to avoid sheltering incumbent industries from disruption beyond what is absolutely necessary to maintain continuity of public goods and services.

4. Decarbonizing the global economy will not be costly, it will instead save trillions of dollars

A widespread misconception is that mitigating greenhouse gas emissions will be expensive in direct economic terms unless the environmental costs of emissions are included in the calculus. In fact, the opposite is true: sheltering the incumbent polluting industries in the energy, transportation, and food sectors from disruption would be a multi-trillion-dollar mistake. If SWB, A-EVs, TaaS, and PF were not economically competitive, we would not be able to rely on market forces to drive the disruptions. Fortunately, these existing technologies are all either already competitive or will be competitive within several years, and continue to become cheaper as their adoption accelerates while costs and capabilities improve with scaling. Investing now in older technologies would be an extremely costly mistake, as the acquired assets will inevitably be stranded within the next decade by the disruptions. For example, our research shows that at least $2 trillion in recent investments made over the last decade in coal, natural gas, and nuclear power assets throughout their value chains will be stranded by the SWB disruption of the energy sector.[4] Instead of protecting incumbent industries whose assets will become stranded within 15 years, policymakers should look to protecting people in these industries so that societies can be best positioned to take advantage of the disruptions as they accelerate.

By leveraging the power of market forces, mitigation of greenhouse gas emissions can be transformed from a costly expense into a lucrative investment at every scale from local to global. Regions, nations, communities, cities, businesses, and investors choosing to embrace and lead the disruptions rather than resist them will reap enormous economic and social rewards as well as environmental benefits. As the manifest economic, geopolitical, and social opportunities of the disruptions, along with the risks of ignoring them, becomes ever clearer, many actors will seek to accelerate their own transformation for reasons beyond climate mitigation alone. Some may do so to mitigate dependence on imported fragile food and energy supplies, while others may recognize the political capital and other benefits to be gained by leading rather than resisting the disruptions. As different actors seek to accelerate the disruptions in their own context to avoid risks or capture a first mover advantage, the ensuing race to the top will generate further powerful accelerating feedbacks that will compound the speed and scale of disruptions worldwide.

5. A focused approach to reducing emissions is better than an all-of-the-above 'whack-a-mole' approach

The evidence to date indicates that it is counterproductive for societies to divide their time, attention, and resources among a large number of different emissions reduction strategies. This all-of-the-above 'whack-a-mole' approach has neither gained widespread social or political support, nor produced meaningful results.

Our analysis shows that the most effective approach is to concentrate on one single strategy: deploy and scale existing technologies to disrupt the energy, transportation, and food sectors as quickly as possible, which will rapidly mitigate the majority of emissions while also making carbon withdrawal through both active reforestation and technology-based approaches affordable (see Box 3: Going Below Zero Emissions). The second and third order cascading effects of these disruptions will also offer previously inconceivable opportunities for environmental restoration that go beyond solving climate change, including problems such as soil and water contamination, air pollution, water shortages, deforestation, biodiversity loss and species extinction, and many others (see Box 6: Disruption Enables All Forms of Ecological Restoration).

6. We no longer need to trade off the environment and the economy against each other

Up until now, economic growth and the stunning progress in human development it has produced have come at the cost of the environment. But this zero-sum game, or win-lose relationship, is not an immutable law of nature, but an unintended consequence of primitive extractive technologies. The specific cost and capability improvements in these existing technologies in the energy, transportation, and food sectors will provide for the first time in history the capacity to do more and more, with less and less, due to the paradigm shift they entail in the fundamental architecture of the production system. Rebound effects notwithstanding, the clean new technologies of SWB, A-EVs, TaaS, and PFCA represent a major step toward the ultimate goal of meeting human needs sustainably. In the case of greenhouse gas emissions, these technologies transform the relationship between the environment and the economy into a nonzero-sum game, or a win-win relationship, by closing the emissions loop entirely and preventing a Jevons paradox from occurring (see Box 2: Mistakes of Conventional Forecasting).[f]

7. The clean disruption of energy, transportation, and food will narrow rather than widen the gap between wealthy and poor communities, and developed and less-developed countries

The conventional approach to mitigating emissions by curtailing economic activity within the existing industrial paradigm would widen the gap between wealthy and poor because human development is almost entirely dependent upon economic prosperity. Instead of depending upon government to control supply and demand, or to achieve equitable distributive outcomes, the technologies of SWB, A-EVs, TaaS, and PFCA will instead accelerate human development and raise the standards of living in poorer communities and less-developed countries by drastically reducing costs of living.

Because energy, transportation, and food are foundational sectors of the global economy, they comprise an outsized share of the cost in virtually every industry's value chain. These new technologies will transform geopolitical relations by eliminating the geographic advantages and disadvantages of the past, such as scarce deposits of fossil fuels to winter storage challenges for food and agriculture, among many others. They will also enable more radical localization, as a new decentralized production system based on creation from abundant local resources supplants the old centralized system.

With the right choices, societies can ensure that the benefits of SWB, A-EVs, TaaS, and PFCA enable poorer communities and less-developed countries to expand and converge with wealthy and developed ones, while planning for and mitigating the impacts of the declining incumbent industries as they are replaced. Moreover, this enormous creation of value will not itself result in any significant increase in emissions because virtually all the demand growth will be met using new clean technologies.

8. The same technologies that allow us to mitigate emissions will also enable us to withdraw carbon dioxide from the atmosphere affordably

Achieving net zero emissions is only the first step toward solving climate change. Having stopped new emissions from entering the atmosphere, we must further address the concentration of carbon dioxide already in the atmosphere, returning it to a safe level. Today the scope and cost of carbon removal seem overwhelming. But the same SWB and A-EV technologies that will disrupt the energy and transportation sectors will also drastically reduce the cost of carbon withdrawal. Active reforestation, ocean alkalinity enhancement (OAE), direct air carbon capture and storage (DACCS), and other carbon withdrawal methods are all costly because of their energy, vehicle (machinery), and labor requirements. These will become much more affordable thanks to SWB super power, electric vehicles and machinery that run on clean electricity, and automated vehicles and machinery that do not require human operators.

We estimate that the cost of carbon withdrawal through both active reforestation and technology-based approaches can fall to under $10 per ton by 2040, which will make it affordable to go below zero emissions, restore carbon dioxide concentrations in the atmosphere to safe levels, and achieve a full solution to climate change (see Box 3: Going Below Zero Emissions).

9. Societal choices matter, and technology alone is not enough to achieve net zero emissions

Although new technology paired with market forces is our most realistic option for achieving net zero emissions as soon as possible, we cannot afford to be complacent. Unless societies make the right choices, we could significantly slow down the disruptions of the energy, transportation, and food sectors, which in turn would dangerously delay the achievement of that goal. Even if negative emissions allow us to remain within a given carbon budget over the longer term, transgressing thresholds and tipping points in planetary systems could still lead to catastrophic consequences, making the risks of delaying by even a few years severe.[44] It is therefore crucial we make the right choices today to accelerate the disruption of energy, transportation, and food.

For sub-sectors of the economy for which mitigation technologies still require research to reach commercial viability, governments along with private investors should provide funding for R&D.

For sub-sectors of the economy for which mitigation technologies are ready for deployment but must be refined through experience and scaling to become competitive, governments need to help design efficient markets with judicious use of regulations, standards, mandates, and prohibitions, as well as provide temporary supports and subsidies to accelerate the phase-in of the new technology. Risk tolerant private investors should finance early growth and refinement to help take the technologies to market.

For sub-sectors of the economy for which mitigation technologies are already deployed and ready to scale, governments should remove market barriers, break up existing monopolies, guarantee consumers rights to produce and trade with the new technologies, and end existing protections for incumbent industries based on older technologies while ensuring protections and opportunities for people in these industries to transition to the disruptive industries. Private investors should finance deployment as the disruption takes off.

Box 6: Disruption Enables All Forms of Ecological Restoration

The very same disruptions of energy, transportation, and food that allow us to address climate change will also enable us to address many of our most entrenched environmental problems. Up until now, the primary reason why we have not done more to prevent new environmental destruction or repair past damage is because the cost was too high. Clean alternatives to polluting industries, cleaning up polluted areas, restoring ecosystems, and conserving large areas of land and the oceans are all prohibitively expensive. But that is about to change. Today, these three disruptions are poised to slash costs and create opportunities for environmental protection and ecological restoration that were previously unimaginable.

Reducing Our Ecological Footprint

The disruptions of energy, transportation, and food will trigger the greatest reduction of humanity's ecological footprint in history.

The overwhelming economic competitiveness of SWB, A-EVs and TaaS, and PFCA technologies will decimate the fossil fuel, animal agriculture, and commercial fisheries industries worldwide, thereby extinguishing some of the core drivers of air and water pollution, soil contamination and loss, deforestation, marine plastic pollution, and terrestrial and aquatic biodiversity loss.

» SWB will slash the resource intensity and ecological footprint of energy by shifting the mode of production from one requiring gigatons of ongoing mining and burning of fossil fuels each year to one in which a standing stock of assets harvest energy directly from the sun and wind.

» A-EVs and TaaS will utilize clean energy directly, and with 5-10 times greater efficiency per vehicle mile travelled than privately-owned combustion vehicles.

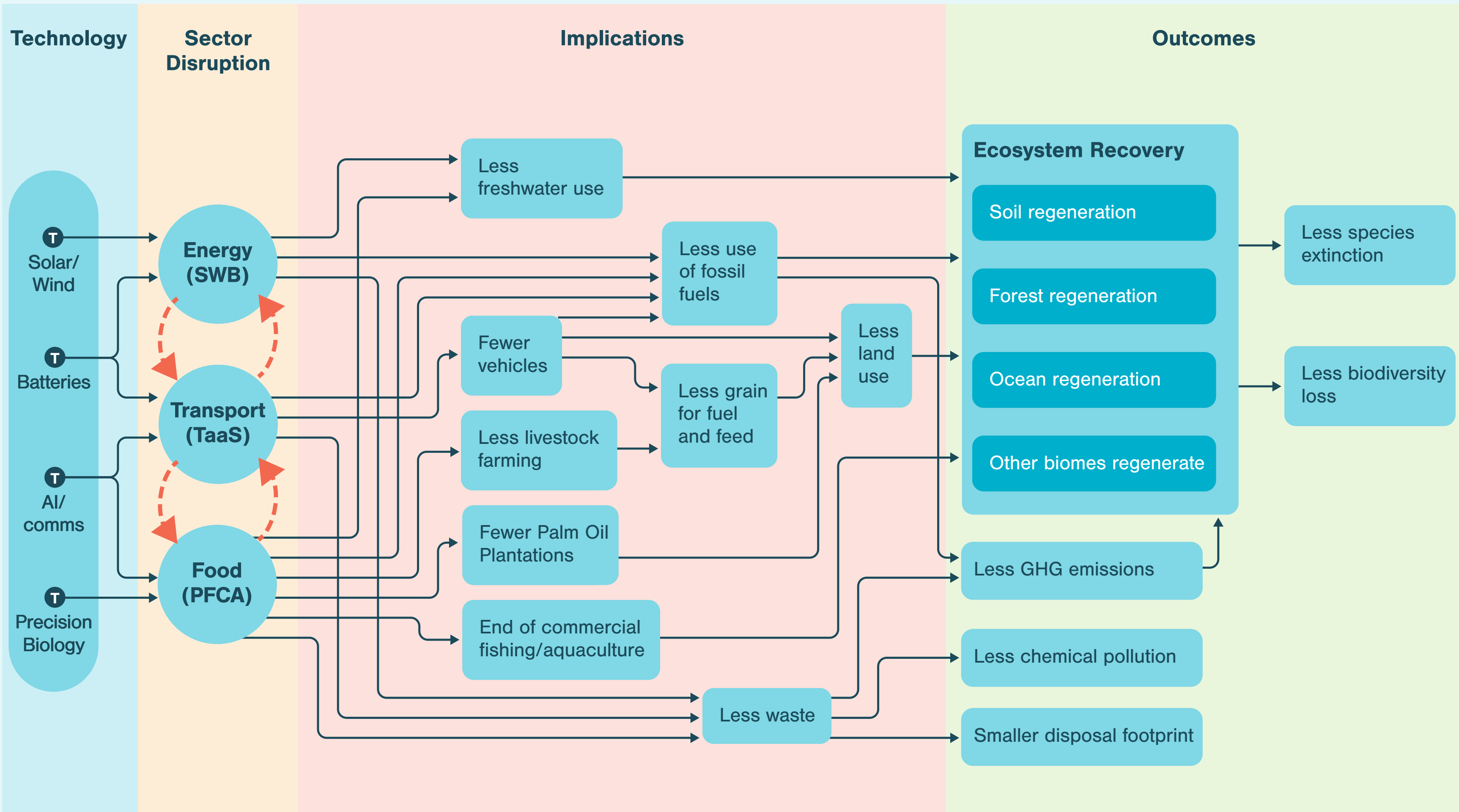
» PFCA will wipe out the livestock industry responsible for an ecological footprint the size of the United States, China, and Australia on land, and remove the underlying drivers of deforestation and ecosystem destruction involving land for pasture, animal feed, or products like palm oil. It will also wipe out the commercial fisheries and aquaculture industries that have devastated the world's coastal and marine ecosystems.

» The ecological footprint of moving commodities from the energy, transportation, and food sectors – coal, oil, natural gas, iron, steel, vehicles, livestock, grain, and seafood – will shrink dramatically.

Unprecedented Opportunity for Ecological Restoration

The disruptions of energy, transportation, and food will dramatically reduce the cost and expand opportunities for environmental conservation and restoration. Although pressure on ecosystems has increased for generations as the ecological footprint of human civilization has expanded, we are approaching an unprecedented moment when the three simultaneous disruptions will trigger an extremely large and sudden decrease in that pressure worldwide for the first time. Governments, communities, and interest groups must therefore begin planning today to take advantage of the enormous opportunities for conservation, rewilding, and ecological restoration that will emerge in the 2020s and 2030s.

Figure 18: Disruption Supports Ecological Restoration



Source: RethinkX.

Appendix A

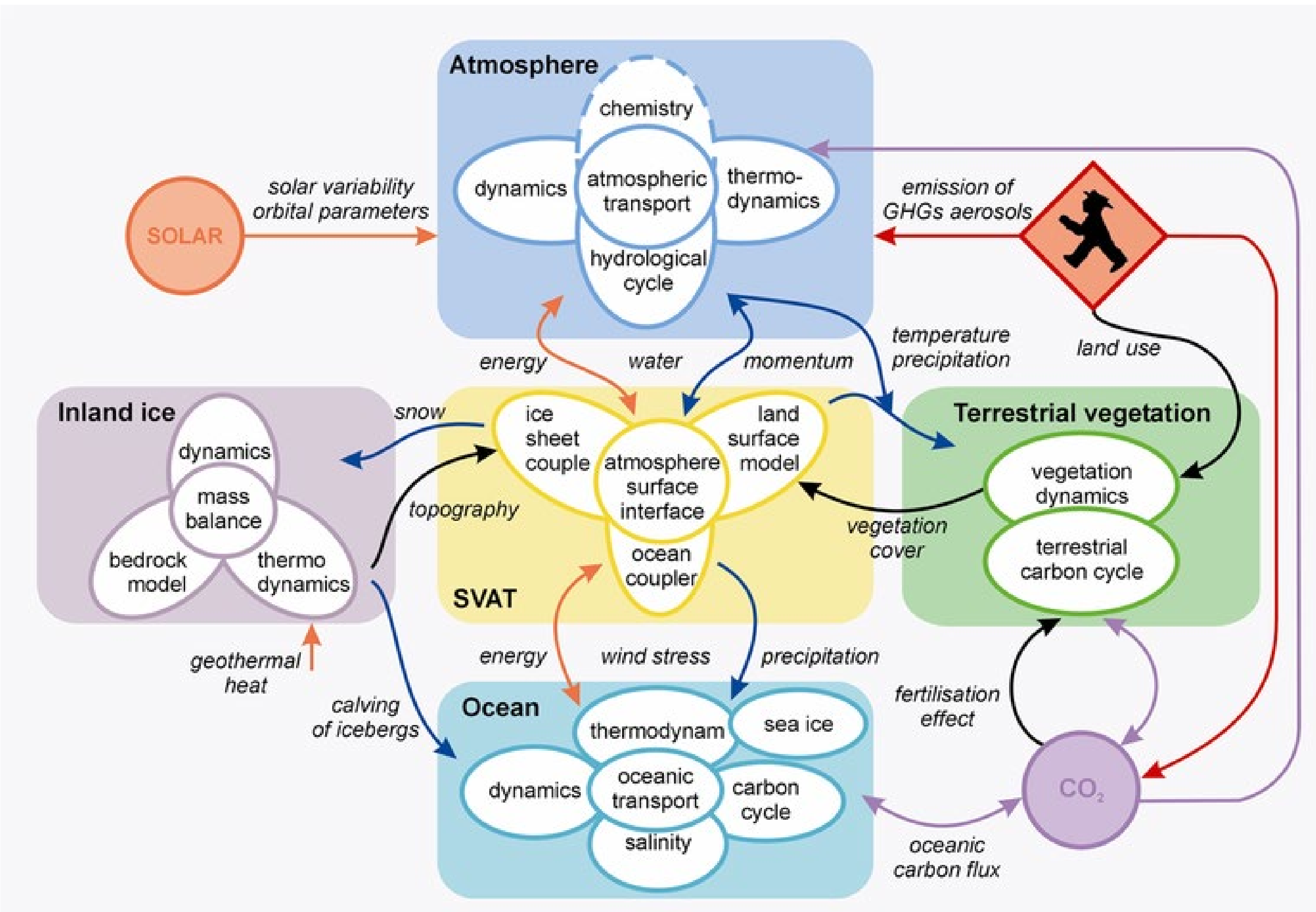
The Climate Challenge

The response of most policymakers to climate change has been constrained by an assumption that it occurs as a slow and incremental process. Since the Industrial Revolution over two hundred years ago, increasing carbon dioxide (CO_2) emissions due to growing exploitation of hydrocarbon energy sources (or 'fossil fuels') has led to a rise in global average temperatures.

Nonlinearity

While most climate change studies have assumed that warming trends are linear, in reality global warming underwent nonlinear acceleration through most of the twentieth century, speeding up since 1980.[45] It is now widely accepted, though still poorly understood, that the Earth's climate system is highly nonlinear, consisting of multiple subsystems existing in states of equilibrium which can undergo episodic, abrupt, and rapid change. Rather than slow and gradual, climate change largely occurs through abrupt, rapid events which punctuate these longer periods of equilibrium.[46]

Figure 19: Systems Dynamics of Climate Change



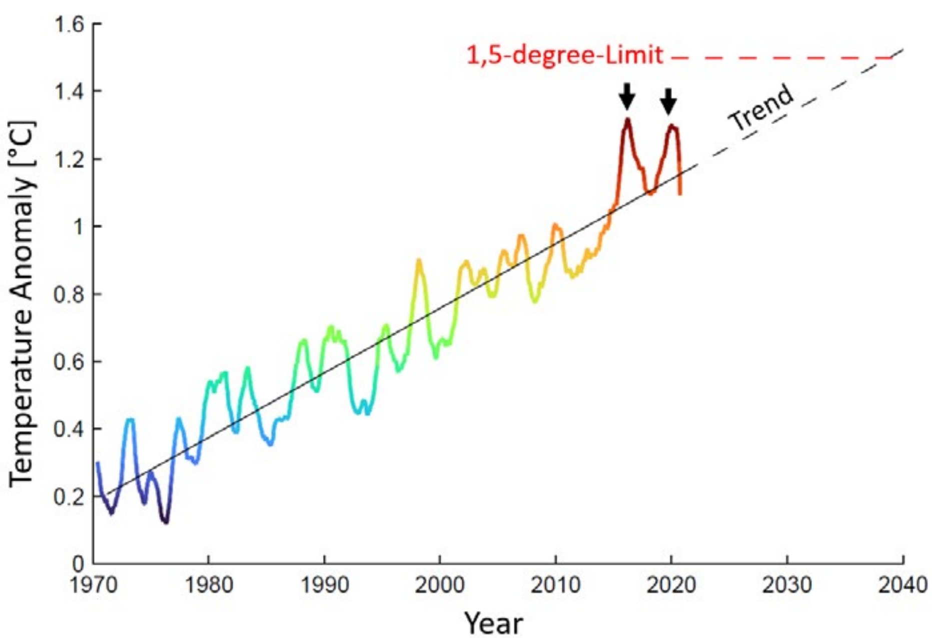
Source: Diagram from Postdam Institute for Climate Impact Research.[47]

While linear systems typically display smooth, predictable and regular motions in space and time, nonlinear systems undergo sharp and disproportionate transitions when states of equilibrium are disrupted by forces that push the system past certain critical thresholds. When forces converge to trigger tipping points that pass these thresholds, the resulting exponential changes can result in a complete transformation or phase change of the climate system culminating in a new equilibrium.[44]

The Earth as a Complex System

The increasing recognition of nonlinear dynamics in earth systems underscores the levels of uncertainties in assessing climate risks. Atmospheric concentrations of CO_2 passed 400 parts per million (ppm) in 2016 and continue to increase, today reaching 414 ppm.[48] The result has been a global temperature increase of approximately 0.2°C per decade, resulting in surface temperatures approximately 1.0°C (1.8°F) warmer than the pre-industrial period.[49]

Figure 20: Global Temperature Increase Since 1970



Source: Chart from Rahmstorf, 2021.[50]

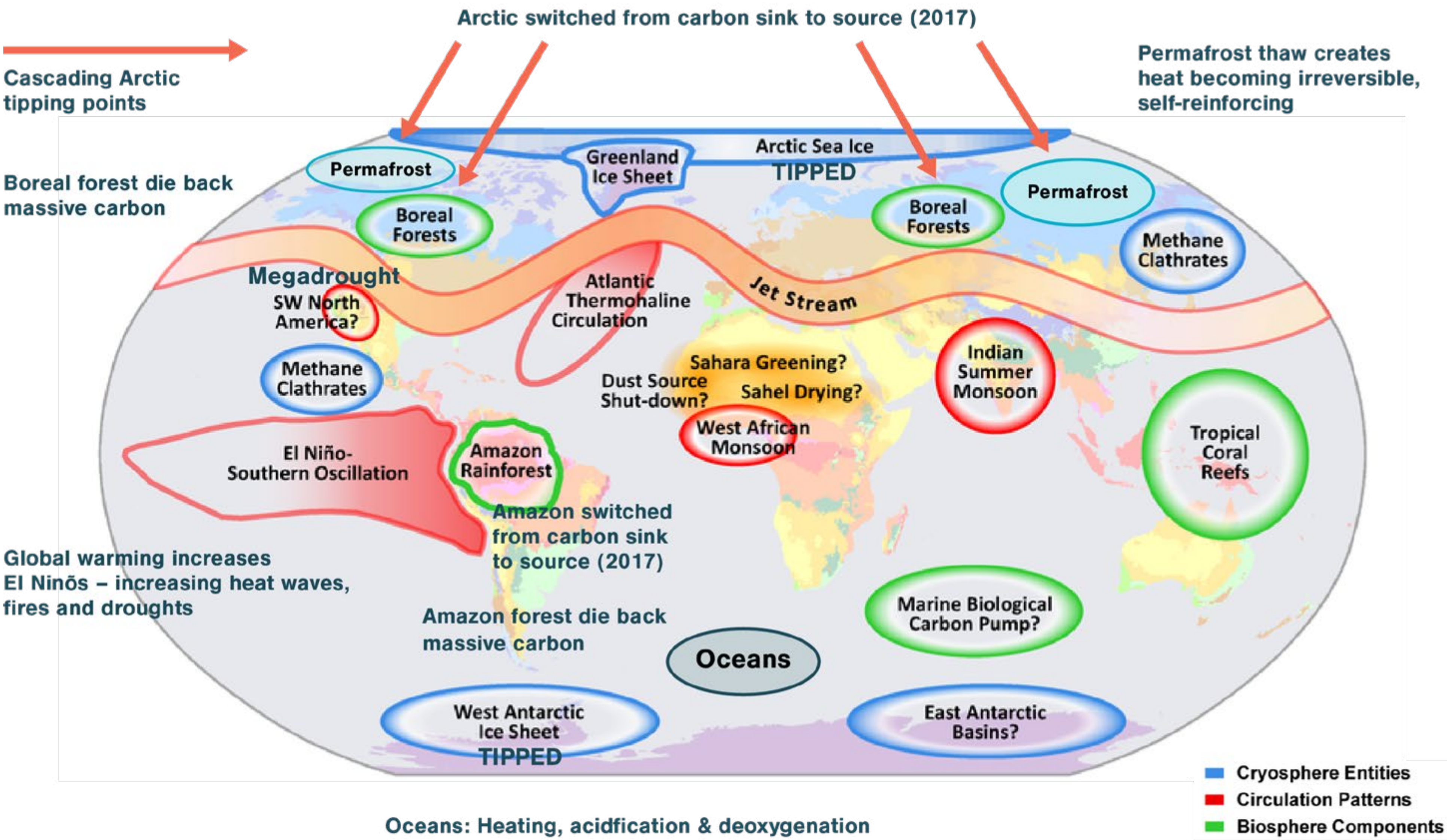
The scientific consensus under the Paris Climate Accord indicates that it is necessary to limit global average temperatures to below 2°C – preferably to 1.5°C – over a 30-year average, to avoid the risk of tipping the climate system over into a more dangerous state. If the current warming trend continues, the planet will breach the 1.5°C threshold by 2040.

However, a growing body of research on climate tipping points indicates that even at current levels of warming, there is a risk that several tipping points may already be crossed with potentially irreversible consequences. In these climate subsystems, small changes in global temperature could trigger amplifying feedback loops that lead to self-reinforcing changes creating a new more dangerous equilibrium.

For example, in the Arctic, we see the ice-albedo effect where warming temperatures decrease snow and ice cover, reflecting less solar radiation back into the atmosphere, increasing the absorption of radiation and therefore increasing the warming effect. This means that global warming is driving a nonlinear increase in regional Arctic temperatures, which in turn feeds back on the overall global warming trend.[51] Many climate models do not fully account for how such amplifying feedbacks can release additional amounts of carbon dioxide and methane when rising temperatures trigger ecological and chemical responses, such as warmer oceans giving off more carbon dioxide, or warmer soils decomposing faster, releasing increasing amounts of carbon dioxide and methane. As a result, the potential level of future warming might be underestimated.[52]

As a result of taking these complex uncertainties into account, scientists have identified ten of the most important climate tipping points: permafrost thaw, loss of methane hydrates from the ocean floor, weakening land and ocean carbon sinks, increasing bacterial respiration in the oceans, Amazon rainforest dieback, boreal forest dieback, reduction of northern hemisphere snow cover, loss of Arctic summer sea ice, and reduction of Antarctic sea ice and polar ice sheets. Even if warming is capped within the 1.5-2°C range, there is a risk that this could drive self-reinforcing feedbacks that push these tipping points toward a planetary threshold leading to a worst-case 'hothouse earth' scenario even as human emissions are reduced, underscoring James Hansen's historic warning that the atmospheric concentration of greenhouse gasses should not exceed 350 parts per million (ppm). As of 2020, this value is well within the heightened risk zone at 409.8ppm.[53]

Figure 21: Global Warming Vulnerable Tipping Points



Source: Diagram from Postdam Institute for Climate Impact Research.[54]

Achieving Net Zero

To mitigate these risks requires keeping global average temperatures well below 2°C over a 30-year average. To do so, the United Nations Intergovernmental Panel on Climate Change (IPCC) suggests, will require global carbon emissions to be reduced by around 50% by 2030, with a view to reach net zero by 2050 through 'negative emissions' to withdraw CO_2 from the atmosphere due to industries where it has not been possible to bring emissions to zero.[12] It is widely recognized that this will require a radical, top-to-bottom transformation of the global economic system, especially our energy, transportation, and agriculture practices,[55] which together account for some 91.6% of global carbon emissions.[13]

However, achieving net zero is not sufficient to secure a complete climate solution. The 'hothouse earth' scenario illustrates that even at the current levels of atmospheric concentration of greenhouse gasses, there is already an unacceptable risk of dangerous climate change with potentially existential consequences. Therefore, a complete climate solution needs to not only halt existing emissions, but to also drawdown the existing stock of carbon in the atmosphere to a safe level below 350 ppm.

This is compounded by recent research suggesting that all the IPCC's net zero decarbonization scenarios out to 2050 are in fact far too slow, and offer a 40-80% probability of at least temporarily going above 1.5°C.[56]

However, conventional forecasts of carbon emission pathways produced by the IPCC and the International Energy Agency (IEA) assume that incumbent carbon-intensive industries comprising the existing production system will largely continue to exist out to 2100, experiencing only a slow and gradual phaseout limited by the bureaucratic inertia of government decision-making. But these scenarios and the net zero pathways they entail are based on fundamentally incorrect assumptions about the technology-driven societal disruptions which are already underway across some of the most critical sectors of the economy. Although these disruptions indicate that far greater emissions reductions will be possible than conventionally assumed, they will not eliminate the risk of dangerous climate change without the right societal choices.

The failure to recognize the nonlinear dynamics of these technology disruptions and their capacity to fundamentally transform the foundations of our present industrial system is rooted in a widespread lack of understanding of how change occurs in human systems, similar to the outmoded assumptions that have constrained conventional understandings of climate change.

Just as the history of the earth system consists of long epochs of equilibrium punctuated by abrupt transformations, human systems similarly experience sudden periods of rapid change which disrupt extended periods of stability. Being accustomed to the incremental conditions of these periods of stability is a key reason that conventional analysts frequently overlook the signals of rapid change.

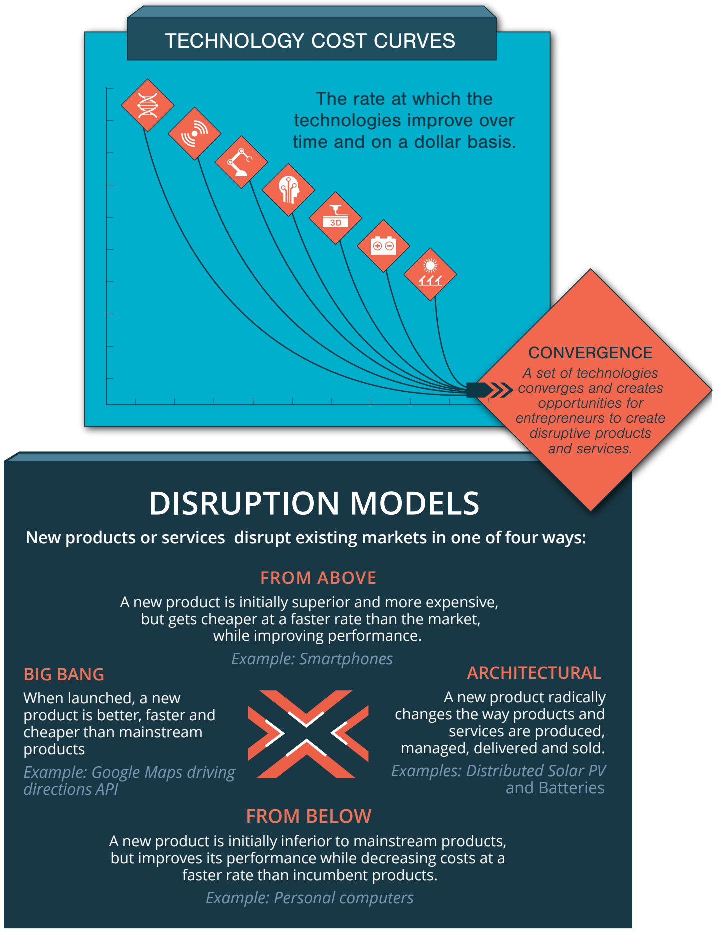
Appendix B

The Seba Technology Disruption Framework

Understanding Technology Disruption

Conventional analysts tend to examine risks and opportunities by extrapolating the present into the future in a straight line. As a result, they largely fail to anticipate the full impacts of societal and technological change. RethinkX uses the Seba Technology Disruption Framework, developed by RethinkX co-founder Tony Seba, to understand technology disruption.

Figure 22: Elements of The Seba Technology Disruption Framework



Source: RethinkX.

A disruption happens when new products and services create a new market and, in the process, significantly weaken, transform, or destroy existing product categories, markets or industries. Disruptive technologies emerge when several technologies, each one improving at a different rate, converge at a certain point in time to make it possible for new products or services to be developed that outperform and outcompete existing products.

The cost and capabilities of disruptive technologies improve exponentially rather than linearly. Market adoption of the new technology grows along a sigmoidal or S-shaped curve as its cost improves. Technology cost-improvement curves show the rate at which a given technology improves over time, driven by a combination of factors, including increased investments, research and development, manufacturing scale, experience and learning effects, openness, competition, standards, ecosystem integration, application across industries and the size of the market(s). By understanding the technology cost curves of the disrupting product, it is possible to predict when the disruption will take place.

The greater value proposition offered by disruptive technologies outcompetes and disrupts any products, services, markets, and industries that are wedded to older technologies. Often disruptive products are not just one-for-one substitutes for the older products. Rather, the new technologies tend to both expand existing markets and create entirely new ones by supporting novel business models and forms of value creation. This is why disruptions tend to confound conventional analysts and industry experts whose forecasts and projections misunderstand the speed, scale, and transformative dynamics of disruptions.

Cross-Sector Cascading Effects of Disruptions

These disruptions across the foundational sectors of energy, transportation and food will not simply be contained to these specific sectors, but by their very nature will have cascading second and third order effects across other sectors.[5] Conventional analysts who often specialize in one sector or another tend to misunderstand the fundamental dynamics of disruption as originating in a convergence of technologies that often come from different sectors, and evolving through cross-sector interactions due to the complex interconnections between all these sectors. These fundamental dynamics of disruption can be understood from well-documented historical examples such as the disruption of the horse by automobiles, or of manuscripts by printed books.

Although horses were the primary mode of transport for thousands of years, at the dawn of the twentieth century a convergence of technologies occurred that led to the abrupt collapse of the once ubiquitous horse and carriage industry within approximately 13 years. Convergence brought together disparate cross-sector innovations in steel and rubber production, the pneumatic tire, the combustion engine, and the assembly line, which ultimately made possible the manufacture of affordable and functioning cars on a mass scale. Despite tremendous barriers to car adoption – lack of paved roads, supply chains or mechanics, manufacturing capacity, and oil wells or refineries – the exponential improvement in costs and capabilities caused what began as a minority niche to rapidly expand. Eventually, the horse and carriage industry entered a death spiral of dwindling demand, escalating costs, plummeting investments, and reversing economies of scales resulting in complete collapse. Most importantly, however, cars did not simply substitute for horses, but created a phase shift scale transformation of the transport system that had cascading cross-sector impacts on food, energy, information, and materials. The new capabilities to affordably travel faster, further, and carry more load generated endless new market opportunities, transforming agriculture, retail, and mining; patterns of habitation and commutes; the design and structure of entire built environments; methods of conflict; geopolitics, and of course, the environment.

Similarly, while manuscripts were the primary mode of written communications for thousands of years, the invention of the printed book in the 1400s led them to become obsolete within mere decades. The printing press came about as a result of the convergence of technologies across multiple sectors: metal, movable type, paper, new inks and an adapted wine press. It led to the cost of book production becoming ten times lower than before, making information cheaply available to a mass audience for the first time in human history. Printed books did not simply substitute for manuscripts, but created a phase shift scale transformation of the information sector that rippled out across other sectors enabling vast new societal changes. The loss of control over information flows by the church and state paved the way for the mass transmission of ideas that eventually led to the Reformation, the separation of church and state, and the Scientific Revolution and Enlightenment. The revolution in ideas played a key role in the emergence of a new understanding of reality, and with it, new visions for social organization around democracy and free market capitalism, which in turn dovetailed with the acceleration of the Industrial Revolution.

These historical examples show that the disruptions of energy, transportation, and food occurring today do not represent fundamentally new phenomena, but instead are merely the most recent cases of a wider phenomenon in the history of technology-driven societal change. They demonstrate that disruptions are not only far faster and more transformative than conventional analysts expect, they are rarely ever contained discretely within one sector, but tend to have ramifying second and third order impacts which ripple out across multiple sectors. Those cross-sector cascading effects, in turn, generate wider system dynamics that can drive further innovations, convergences and disruptions in different sectors which can create whole new business models, value chains, cultural and ideological vistas, as well as social, political, and economic systems. These wider system dynamics can further catalyze or inhibit further technology disruptions.

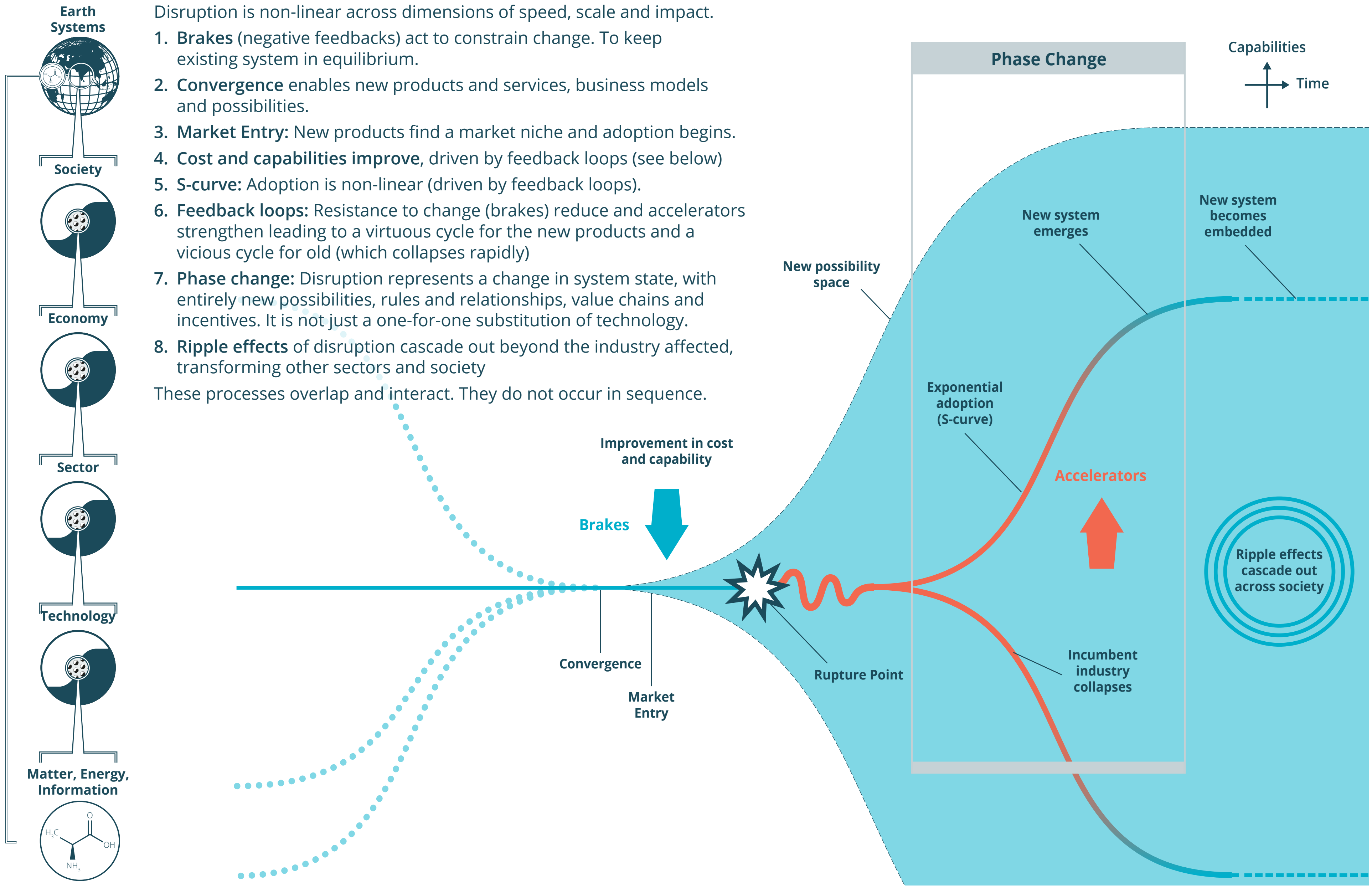
How Disruptions Transform Sectors of the Economy

Figure 23: Understanding Disruption

Disruption is non-linear across dimensions of speed, scale and impact.

1. **Brakes** (negative feedbacks) act to constrain change. To keep existing system in equilibrium.
2. **Convergence** enables new products and services, business models and possibilities.
3. **Market Entry:** New products find a market niche and adoption begins.
4. **Cost and capabilities improve**, driven by feedback loops (see below)
5. **S-curve:** Adoption is non-linear (driven by feedback loops).
6. **Feedback loops:** Resistance to change (brakes) reduce and accelerators strengthen leading to a virtuous cycle for the new products and a vicious cycle for old (which collapses rapidly)
7. **Phase change:** Disruption represents a change in system state, with entirely new possibilities, rules and relationships, value chains and incentives. It is not just a one-for-one substitution of technology.
8. **Ripple effects** of disruption cascade out beyond the industry affected, transforming other sectors and society

These processes overlap and interact. They do not occur in sequence.



Source: RethinkX.

As these cases demonstrate, contrary to conventional assumptions technology disruptions do not follow linear trajectories of incremental change, but are non-linear across dimensions of speed, scale, and impact. As costs and capabilities improve, this drives a series of feedback loops and ripple effects that lead to accelerating adoption which rapidly outcompetes incumbent industries. The following identifies some of the key processes that work at different stages of disruption.

» **Brakes** (negative feedbacks) act to constrain change within an existing system. They consist of prevailing structures, forces, beliefs, and behaviours which act together to maintain the system in a state of equilibrium, and are therefore resistant to change. Change within an existing system subject to these brakes is linear and incremental.

» The **convergence** of multiple technologies in a sector enables the innovation of new products and services, business models and manufacturing methods which offer entirely new dynamics and possibilities to that of incumbent products and industries.

» **Market entry:** When the new products find a market niche that satisfies specific needs, and are capable of meeting demand in superior ways, adoption begins at pace. There are four different ways in which new products disrupt existing markets: 'From Above' – a superior product starts more expensive but becomes cheaper faster than the market while improving performance; 'From Below' – an inferior product improves performance and becomes cheaper at a faster rate than incumbent products; 'Big Bang' – a new product launches with superior performance, faster and cheaper than mainstream products; 'Architectural' – a new product radically changes how products and services are produced, managed, delivered and sold.

» Disruptive technologies experience **cost and capabilities improvements** driven by feedback loops (see below) which consist of simultaneous increases in production quality and performance, alongside decreases in costs, making the products increasingly competitive with incumbent industries.

» As the new products begin to capture the market, disruption reaches a **rupture point**, following which the existing system associated with incumbent industries and markets begins to break down. However, at this point, a new system has not yet emerged. Market trauma occurs when the competitive dynamics of the new products and business models they entail have early and disproportional impacts on the finances and business models of incumbent products and industries. After the rupture point, old metrics used to measure performance and efficiency of incumbent industries become increasingly antiquated and irrelevant as they are designed for systems and markets which are breaking down. New metrics and measurement categories are required for the new industries and systems. For example, LCOE (Levelized Cost of Electricity) metrics associated with conventional power plants and which once vindicated their performance are premised on flawed and narrow assumptions about these systems that ignore the dynamics of solar, wind and batteries. When corrected for those flaws, LCOE for conventional power plants is far higher than previously assumed by major institutions.[57]

» **S-curve:** As costs and capabilities of the new products improve and becoming increasingly competitive with, and eventually outcompete, incumbent products and industries, their mass adoption accelerates in a non-linear process. Driven by feedback loops, this process begins slowly at first, then gradually picks up speed before accelerating exponentially and levelling off as the market approaches saturation.

- **Feedback loops:** The structures and forces resistant to change (brakes) associated with incumbent industries become weaker while the competitive dynamics of new products and industries accelerates. This further drives an accelerating **virtuous cycle** of cost and capability improvements for the new products and a **vicious cycle** of escalating costs, declining capabilities, and diminishing returns, or an **economic death spiral**, for the incumbent industries. As a result, as mass adoption of disruptive technologies undergoes non-linear acceleration, this feeds back into incumbent industries experiencing a nonlinear acceleration in their collapse trajectory. The accelerating collapse of incumbents in turn feeds back into the accelerating adoption of the new. In short, both adoption of the new and collapse of the old occur rapidly after the rupture point in a causal **feedback loop**.
- **Phase change:** With mass adoption of the new products and services, an entirely new set of associated rules and behaviours different to the old system becomes dominant. Disruption therefore represents a fundamental change in system state, with entirely new possibilities, success metrics, rules and relationships, value chains and incentives. This is not just a one-for-one substitution of technology, but a complete replacement of the old equilibrium with an entirely new system which will therefore have its own second and third order effects across its own and other sectors.
- With a phase change in the system that defines a particular sector, **the ripple effects** of disruption are not contained to one technology or sector, but inevitably cascade out beyond the industry affected, transforming other sectors and society. Depending on the nature of these transformations and the sectors affected, this can result in wider changes to the entire production and organizing systems of a society or civilization (see next section).

How Disruptions Transform Whole Societies

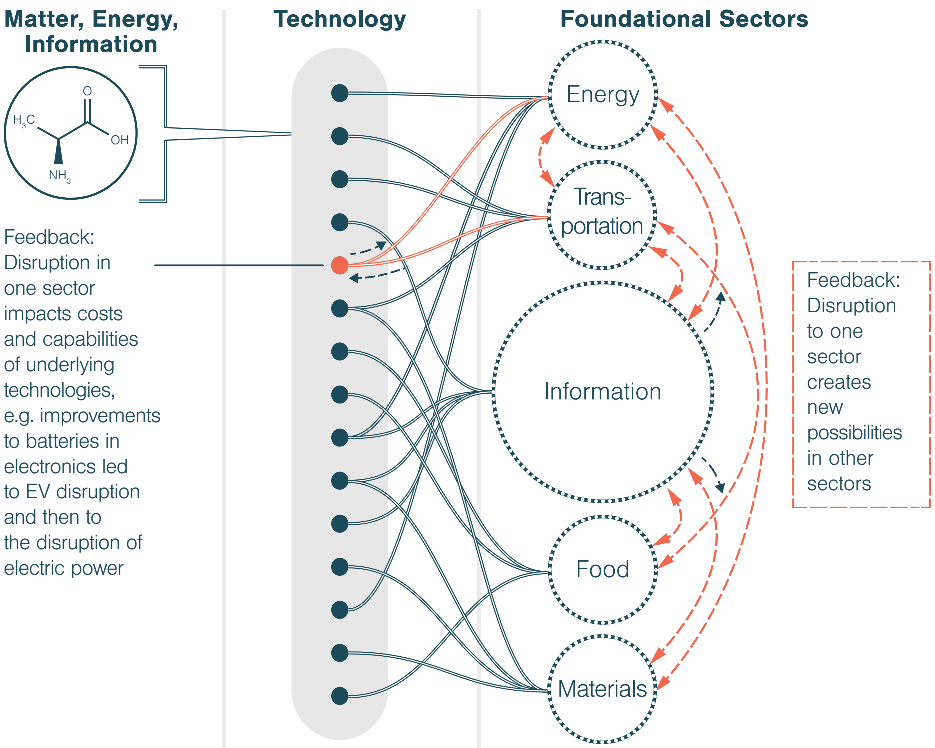
At a certain level of impact, disruption across multiple sectors can create multi-sector phase changes that can reshape the entire higher order system that they are part of. Multiple phase changes across interconnected systems can, therefore, generate a higher order transformation across the whole system of systems. This has profound implications for the potential for wider societal and civilizational impacts of disruptions.

Any human civilization can be defined by two higher order sub-systems, its *production system* and o*rganizing system*.

Every civilization is built from a production system made up of five foundational sectors: how we create and share knowledge (information), eat (food), get around (transport), power ourselves (energy) as well as extract and make things (materials). The production system supplies a society's material needs. These sectors are foundational because they can be found at the core of all other sectors of a society, which are in fact their sub-sectors.

If a civilization experiences simultaneous changes across all five of its foundational sectors of production, the combination of phase changes, ripple effects and feedback loops within and between these sectors can culminate in transformation of the whole system of production. Multiple, simultaneous interconnected technology disruptions across all five sectors therefore entails the rapid emergence of a whole new production system, along with the collapse of the entire incumbent production system. This also entails phase changes, ripple effects and feedback loops between a society's production and organizing systems.

Figure 24: Key Technologies, Convergence, and Interaction Between Sectors



Keys technologies include:
AI, Computing, Precision Biology, Sensors/IoT, Batteries, Solar PV, Communications, Blockchain, Robotics, Additive Manufacturing

Source: RethinkX.

RethinkX has charted simultaneous disruptions in three of the five foundational production sectors, energy, transportation, and food, which at current rates of cost and capability improvements will eventually attain ten times lower costs than incumbent extraction age industries today within the next 10-20 years, rendering them uncompetitive and ultimately obsolete. These disruptions are intimately interconnected to unfolding disruptions in the two other foundational production sectors, information and materials, whose ripple effects have cascaded out across these sectors. The implication is that human civilization has entered an unprecedented period in which all five foundational sectors of production are indeed experiencing disruption, entailing the mass adoption of entirely new 'creation age' products and services in energy, transportation, food, information, and materials.

The new rules, possibilities and dynamics of these products and services imply fundamental phase changes in and across these sectors. Instead of relying on breakdown and extraction of scarce natural resources like coal, oil, steel and livestock, the emerging new production system will be premised on build-up and creation from the limitless building blocks of photons, electrons, molecules, genes and bits.

A society's organizing system co-evolves with its production system and defines how it understands the world and governs behavior, encompassing models of thought, belief systems, social systems, political systems, economic systems, and governance structures which impact ways of thinking, seeing and making decisions at individual, institutional and collective scales. The ultimate design of the production system will be indelibly based on choices and decisions relating to how we design the different elements of our organizing system. Our current organizing system is structured around the needs of the industrial extraction-age production system, and is therefore not optimized around the dynamics and possibilities of a different production system. The decisions we make at the organizing system level will therefore be crucial in determining the ultimate design and possibilities of the technology-driven societal disruptions currently underway.

The nonlinear trajectories of these disruptions imply that human civilization has entered an unprecedented era of profound transformation that will lead to the rapid demise of the extraction age, opening up new opportunities with tremendous implications for all areas of society. However, optimizing for these opportunities will also require fundamental transformations of our organizing system. For this reason, the societal choices we make in the next decade, the design and structure of our organizing system, will be instrumental in determining the rules, possibilities, and opportunities for civilization.

The Age of Creation

Humanity is on the cusp of the most profound transformation of the system of production in human history; from an extraction-based system dependent on exploiting scarce inputs (resources and labor) that requires scale and reach and centralization; to a creation-based system; a generative model that creates the things we need from super-abundant inputs available everywhere, and that is distributed, interconnected and networked.

The complex problems in society, from climate change to conflict and inequality, are an inevitable outcome of this extraction-based system of production. In an extractive system, a 'growth imperative' is the key underlying evolutionary driver. Civilizations that grow their capabilities and reach the fastest, spread through conquest or mimicry. Zero-sum competition forces societies to exploit or be exploited, hardwiring environmental degradation and inequality into the system. Societies that fail to exploit people and the planet slow progress and become footnotes in history. Thus, all these problems are at their root an outcome of our extraction-based system of production.

However, society is blind to this critical insight and the possibility of an alternative. Our reductionist, narrow, linear mindsets mean we fail to appreciate the complex processes of change driving the disruption of our production system and are hence unable to recognize the speed, scale and impact of this transformation. This failure means we see these problems as 'wicked' intractable issues with no good solutions. That might be true within the framework of the incumbent system, where zero-sum trade-offs mean that solving climate change for example, impacts economic growth; but this is not the case in the emerging system, that allows us to address all our problems together without trade-offs, as if cutting the Gordian knot.

Unfortunately, conventional blindness to this opportunity compels us to focus our efforts on solving yesterday's problems, by patching up the old system through 'Band-Aid' solutions which address the symptom not the cause. While many of these 'Band-Aids' have some use in holding the current system together to prevent collapse before the new system emerges, they must not be mistaken for 'cures'. Other 'Band-Aids,' however, can divert valuable resources (time, attention and capital) away from the optimal interventions and even risk shutting off the route to breakthrough.

The impending transformation of the production system driven by disruptions across the five foundational sectors of civilization represents a phase change: a fundamental change to the system state where all the conditions, rules and relationships are re-configured. This system thus cannot be understood through our existing mindsets, nor governed by our existing organizing system. This is why disruption comes from the edge. The greater the expertise of the current system, the more there is to unlearn. The advantage of incumbency will become the baggage of incumbency. Only by relinquishing our reductionist mindsets and embracing a lens built on complexity and holism can we hope to identify the root cause of our problems and seize the extraordinary opportunities emerging allowing us to avoid catastrophic risks.

Our hope is that this work will help reframe debates across society and help us recognize the possibilities of a new system. If we can learn to see the world through a broader, clearer lens, we can properly diagnose our problems so that we can prescribe the right medicine, and avoid making decisions that waste valuable resources on misguided interventions.

Appendix C

Data and Methods

Data

We adopt the GHG emissions sources schema utilized by the Our World In Data project.[13] This project is run by the University of Oxford, and compiles data from the Global Carbon Project, Climate Watch Portal, Climate Data Explorer (formerly CAIT), BP Statistical Review of World Energy, World Bank World Development Indicators, United Nations, Gapminder, and the Maddison Project Database. This schema organizes emissions by sector and sub-sector of the global economy, reflecting their end uses (Table 1).

The baseline year for the data is 2016, and our analysis timeframe begins in 2020. Our modeling and scenarios are constructed in proportion to 2020 emissions, and are thus reported as percentage (%) values rather than as carbon dioxide equivalent (CO_2e) values. This is because the disruption of the energy, transportation, and food sectors will occur on a proportional basis rather than on an absolute basis.

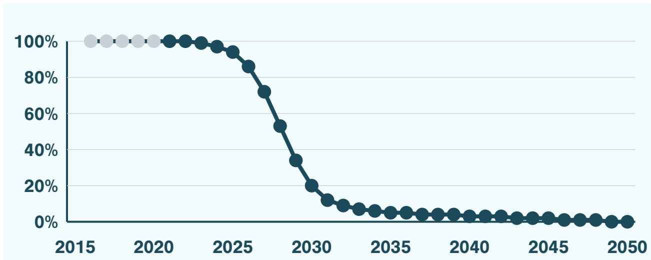
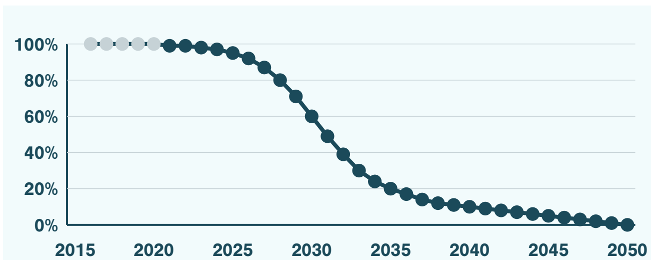
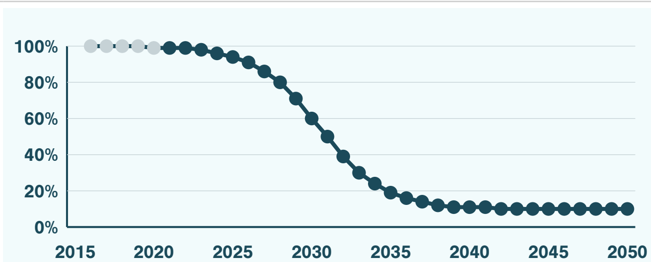
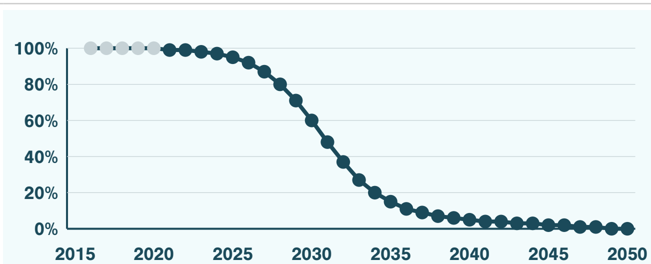
Methods

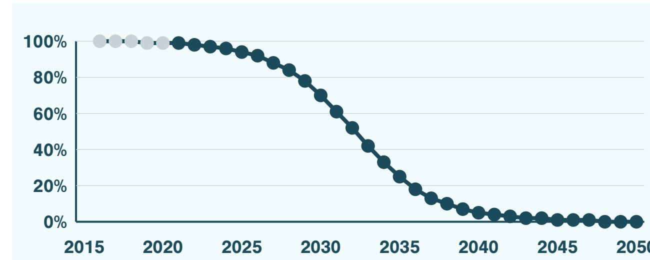
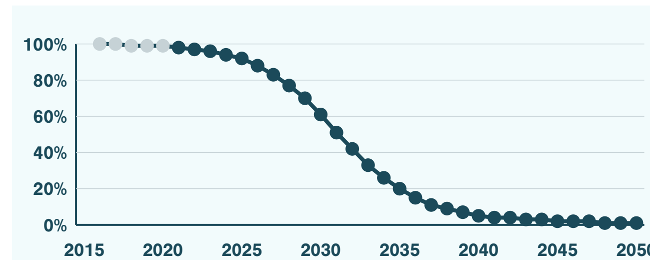
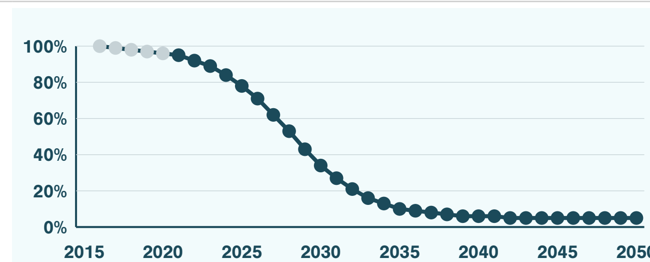
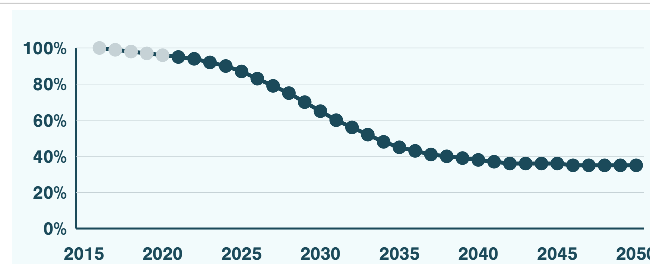
For each sub-sector we assume an emissions mitigation pathway driven by the disruption of the energy, transportation, and food sectors by SWB, A-EV and TaaS, and PFCA technologies, respectively. These pathways are decay S-curves, as shown in Table 3.

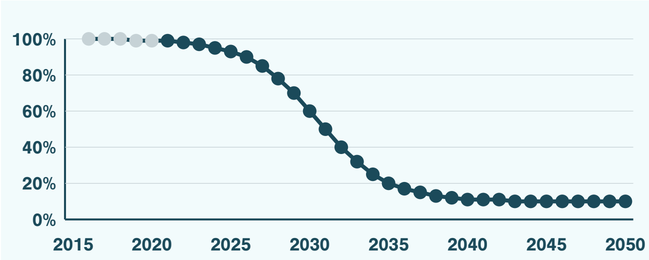
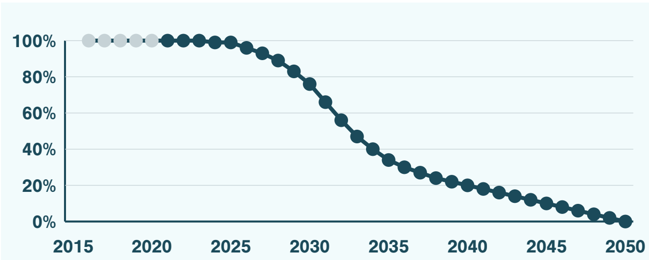
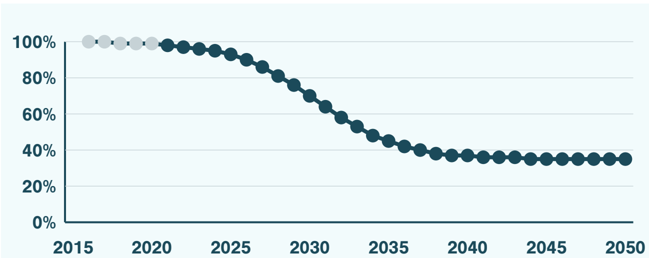
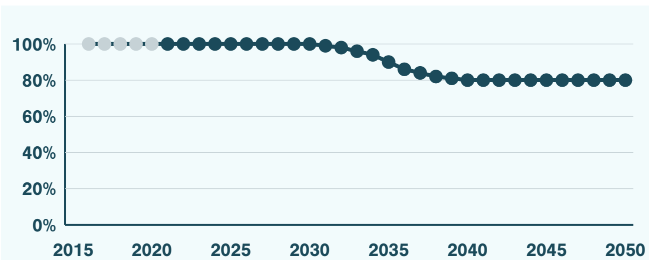
The specifics of each sub-sector's mitigation pathway S-curve are determined by assumptions about how soon disruption will commence, how rapidly disruption will unfold, how completely the incumbent technologies will be disrupted, and any significant niche markets that remain after the disruption has run its course.

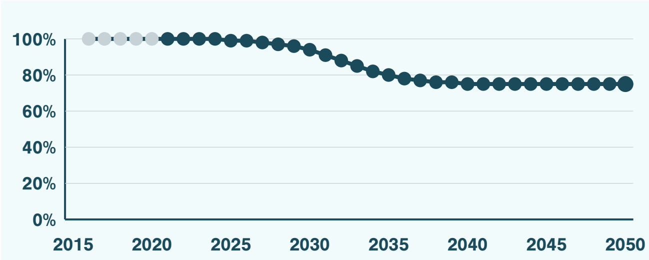
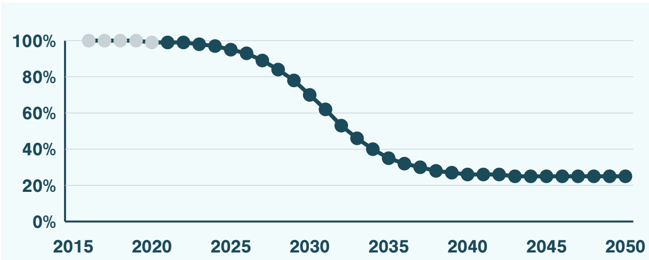
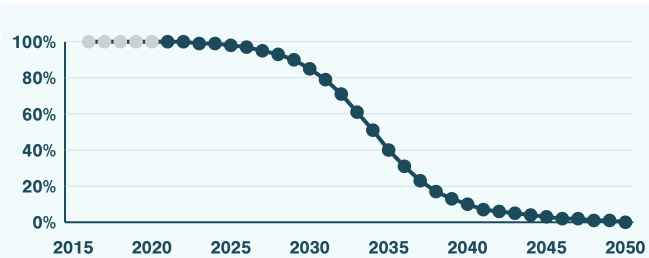
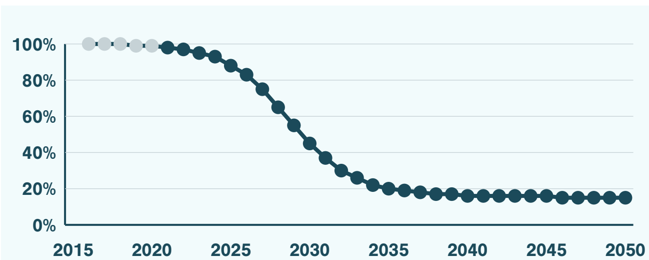
Emissions Mitigation

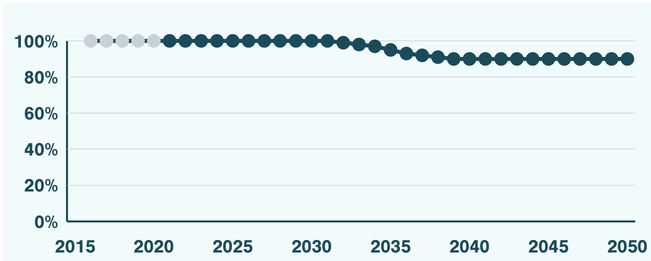
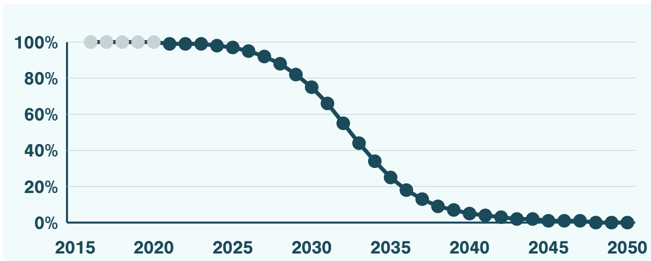
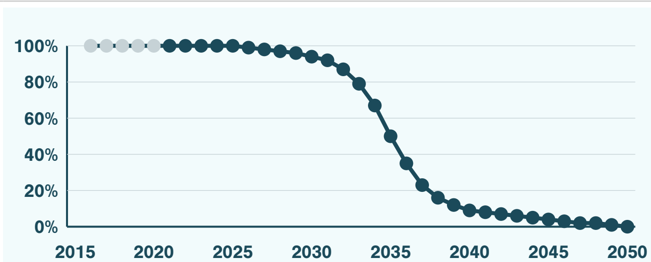
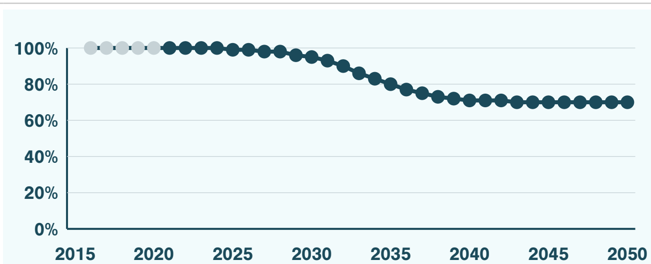
Table 3: Emissions Mitigation by Sub-Sector

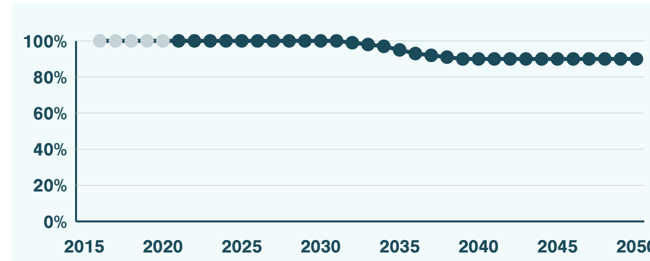
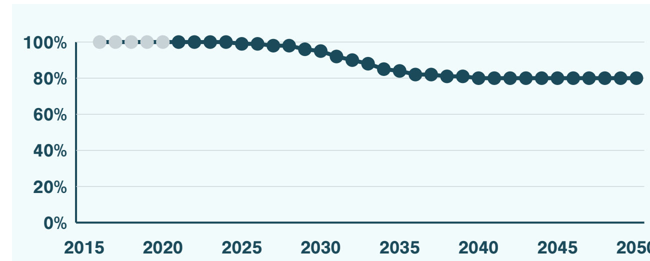
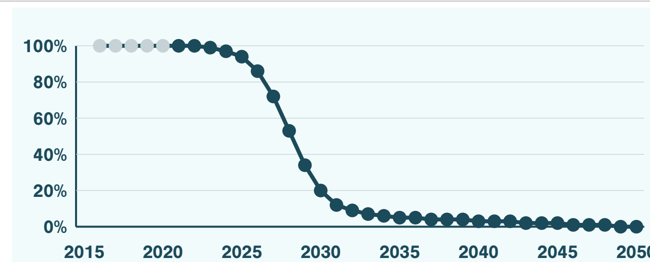
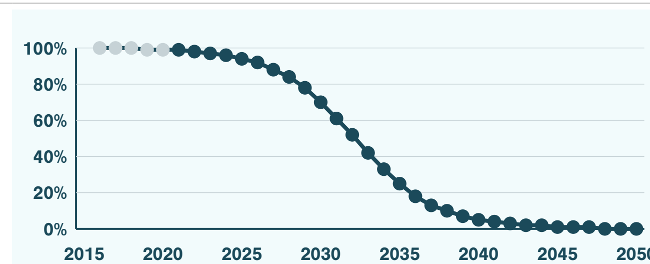
Sub-sector	RethinkX Emissions Mitigation Pathway
Road Transport	
Residential Buildings	
Energy in Other industry	
Unallocated fuel combustion	

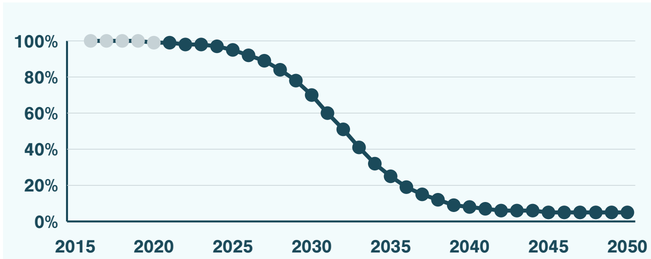
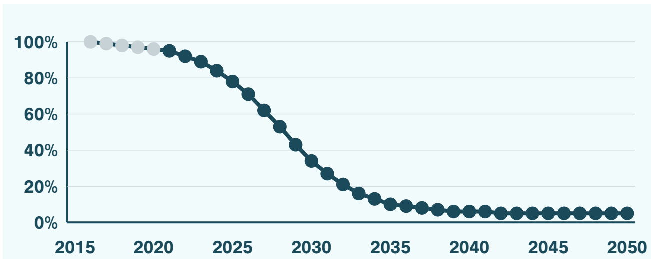
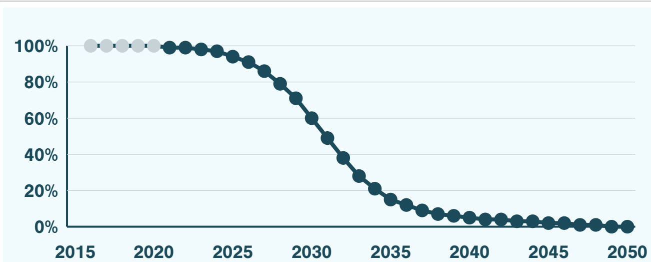
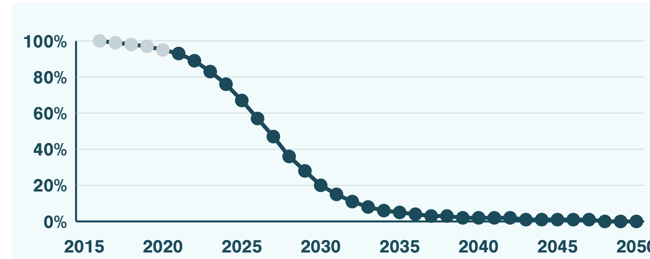
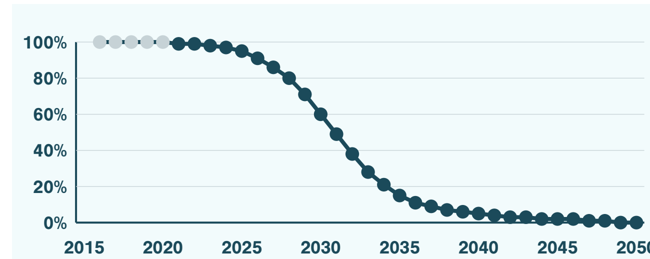
Sub-sector	RethinkX Emissions Mitigation Pathway
Iron & Steel	
Commercial Buildings	
Livestock & Manure	
Agricultural Soils	

Sub-sector	RethinkX Emissions Mitigation Pathway
Fugitive Oil & Natural Gas	
Chemical & petrochemical (energy)	
Crop Burning	
Cement	

Sub-sector	RethinkX Emissions Mitigation Pathway
Chemical & petrochemical (industrial)	
Deforestation	
Aviation	
Fugitive Coal	

Sub-sector	RethinkX Emissions Mitigation Pathway
Landfills	
Energy use in Agriculture & Fishing	
Shipping	
Cropland	

Sub-sector	RethinkX Emissions Mitigation Pathway
Rice Cultivation	
Wastewater	
Energy use in food & tobacco	
Non-Ferrous metals	

Sub-sector	RethinkX Emissions Mitigation Pathway
Energy use in paper and pulp	
Energy use in machinery	
Rail	
Pipeline	
Grassland	

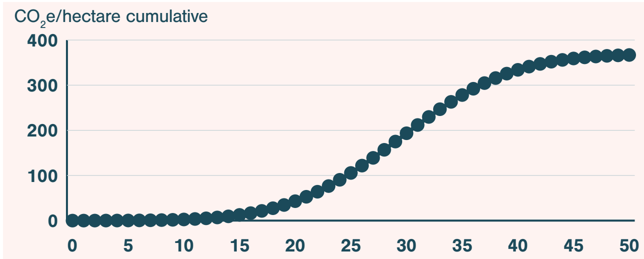
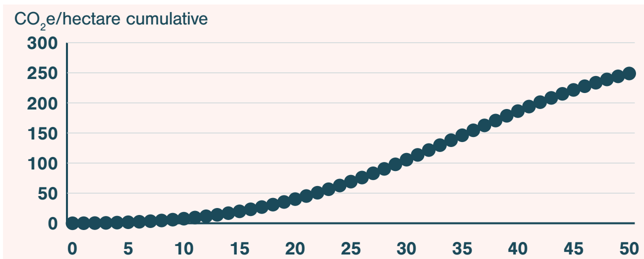
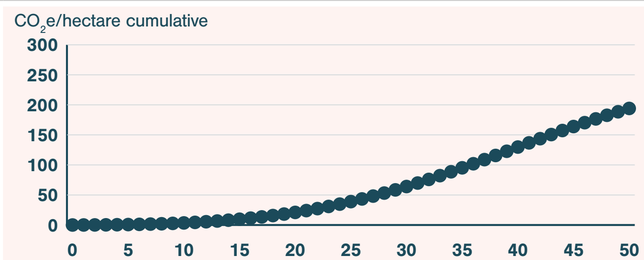
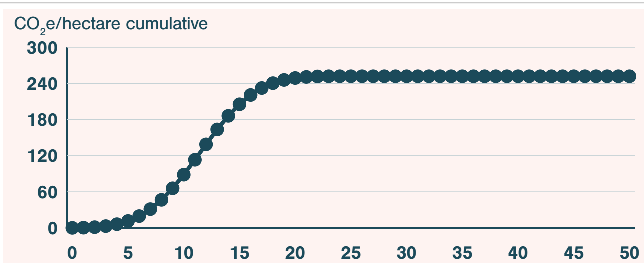
Source: RethinkX.

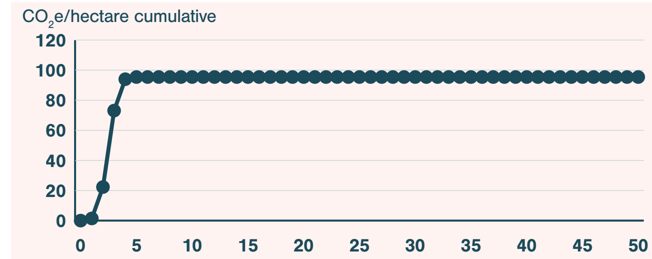
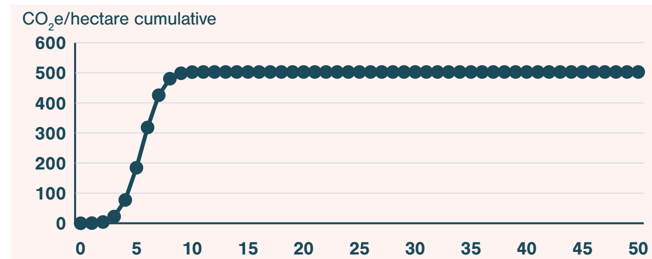
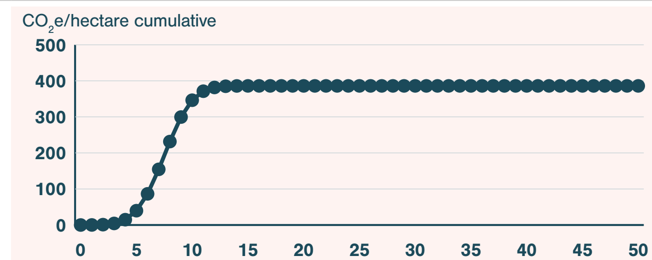
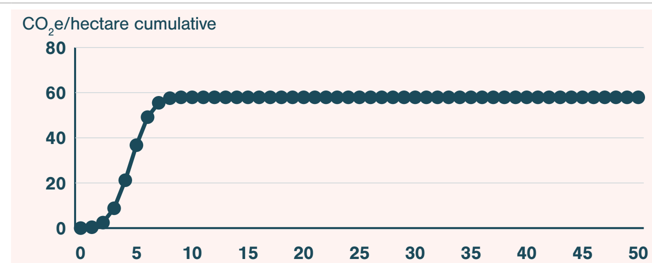
Reforestation

Reforestation plays a significant role in our scenarios. We estimate that the disruption of food by precision fermentation and cellular agriculture (PFCA) technologies will free up 80% of the 3.3 billion hectares of total land area currently devoted to animal agriculture, or a total of 2.7 billion hectares – an area the size of the United States, China, and Australia combined. Even if no active measures were taken to reforest this land, its natural recovery would still result in substantial carbon sequestration in above ground and below ground biomass. And if active measures are taken, the rate of carbon sequestration can be significantly greater. We refer to these as *passive reforestation and active reforestation,* respectively.

We model both passive reforestation and active reforestation of freed land by biome. Note that the rate of carbon sequestration is not constant over time, which results in S-curves for cumulative carbon sequestered that vary dramatically by biome (Table 4 and Table 5).

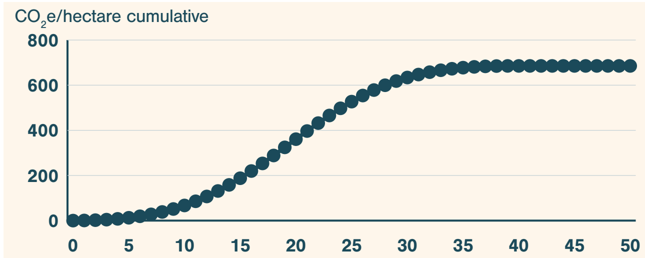
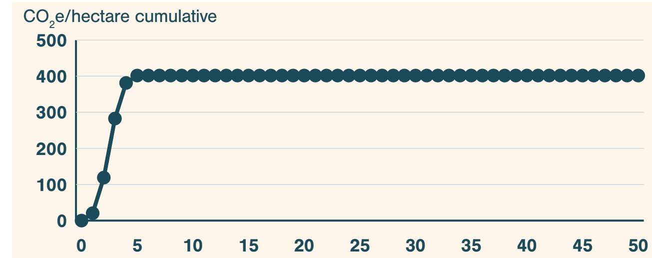
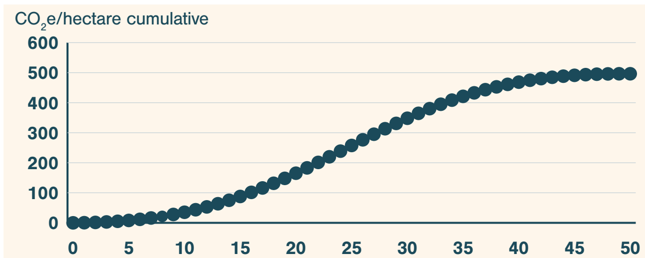
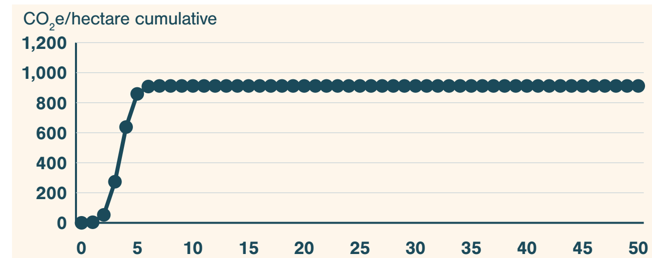
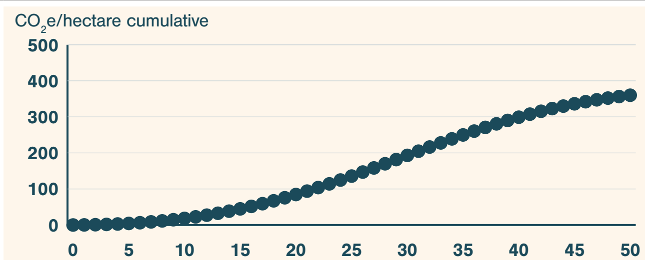
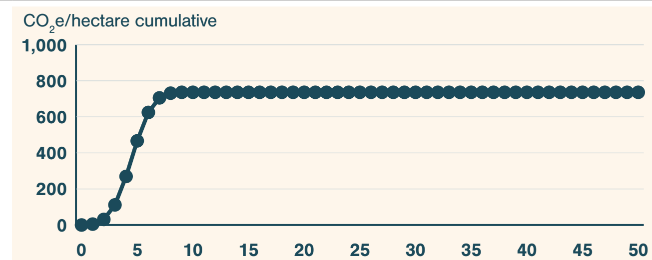
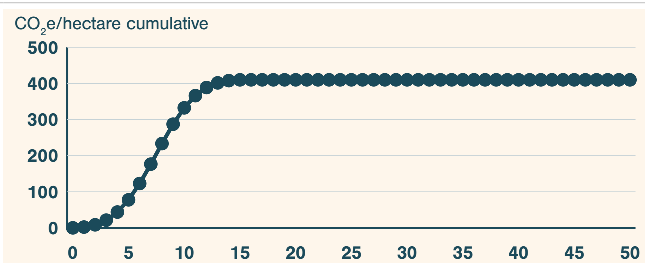
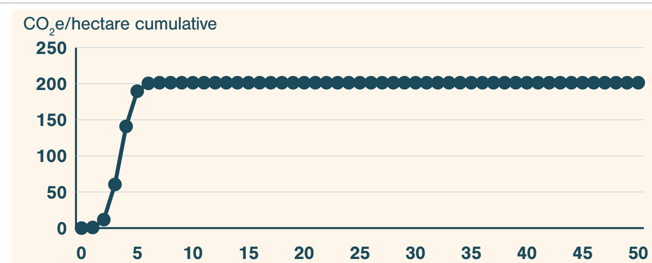
Table 4: Passive Reforestation Carbon Withdrawal by Biome (cumulative CO_2e per hectare)

Biome	Passive Reforestation (cumulative CO_2e per hectare)
Tropical Forest	
Temperate Forest	
Boreal Forest	
Savanna	

Biome	Passive Reforestation (cumulative CO_2e per hectare)
Grassland	
Dense Shrubland	
Open Shrubland	
Desert	

Source: RethinkX.

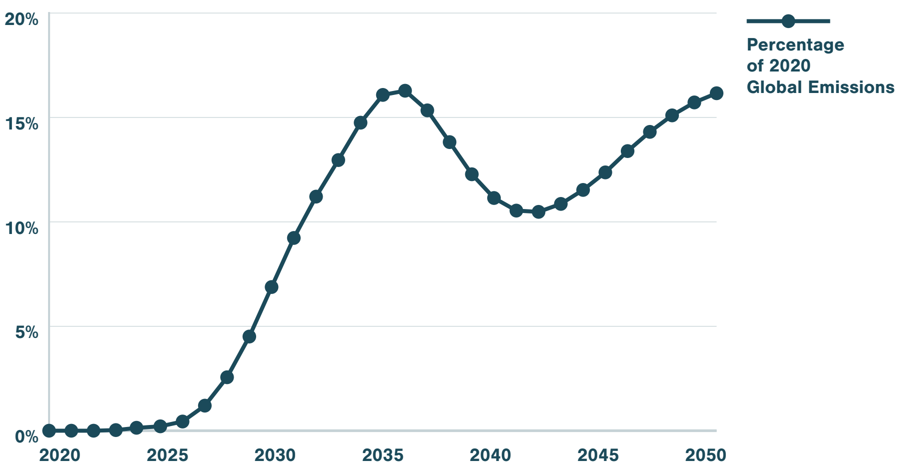
Table 5: Active Reforestation Carbon Withdrawal by Biome (cumulative CO_2e per hectare)

<table>
<tr><th>Biome</th><th>Active Reforestation
(cumulative CO_2e per hectare)</th><th>Biome</th><th>Active Reforestation
(cumulative CO_2e per hectare)</th></tr>
<tr><td>Tropical Forest</td><td></td><td>Grassland</td><td></td></tr>
<tr><td>Temperate Forest</td><td></td><td>Dense Shrubland</td><td></td></tr>
<tr><td>Boreal Forest</td><td></td><td>Open Shrubland</td><td></td></tr>
<tr><td>Savanna</td><td></td><td>Desert</td><td></td></tr>
</table>

Source: RethinkX.

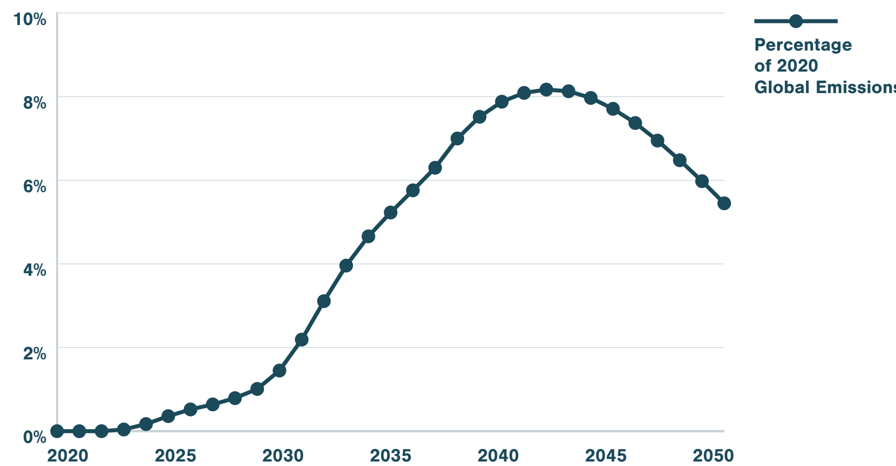
The sum of sequestration across all biomes is shown for passive reforestation in Figure 25, and for active reforestation in Figure 26. Note that because grassland, shrubland, and desert reach their maximum sequestration level much sooner than forests, there is an initial peak in the total sequestration rate followed by a decline and then an increase again. This is particularly evident for passive reforestation, because without active management forests can take several decades to reach their peak sequestration rate and over a century to reach their maximum sequestration level.

Figure 25: Passive Reforestation Carbon Withdrawal by Year – 'Get Serious' Scenario



Source: RethinkX.

Figure 26: Active Reforestation Carbon Withdrawal – 'Get Serious' Scenario

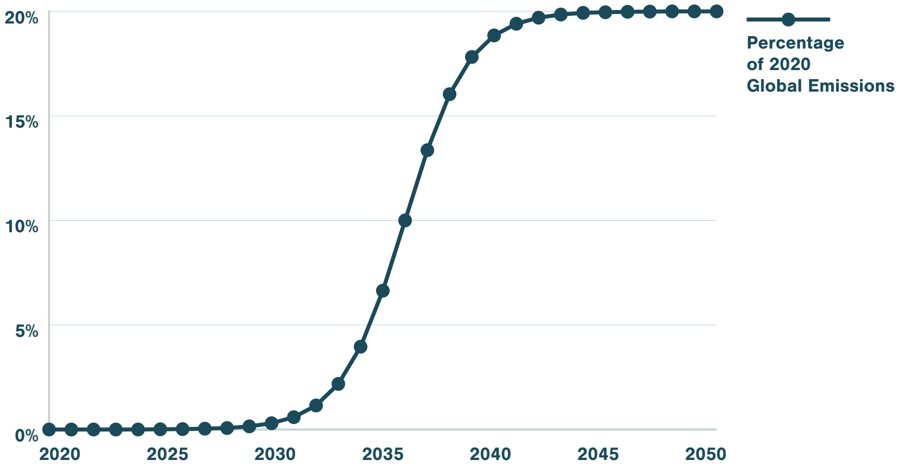


Source: RethinkX.

Technology-based carbon withdrawal

Carbon withdrawal through technology-based approaches features as part of our 'Get Serious' scenario. The quantity of carbon withdrawal scales upward on an S-curve, facilitated by the underlying disruptions of energy and transportation (Figure 27).

Figure 27: Technology-based Carbon Withdrawal by Year – 'Get Serious' Scenario

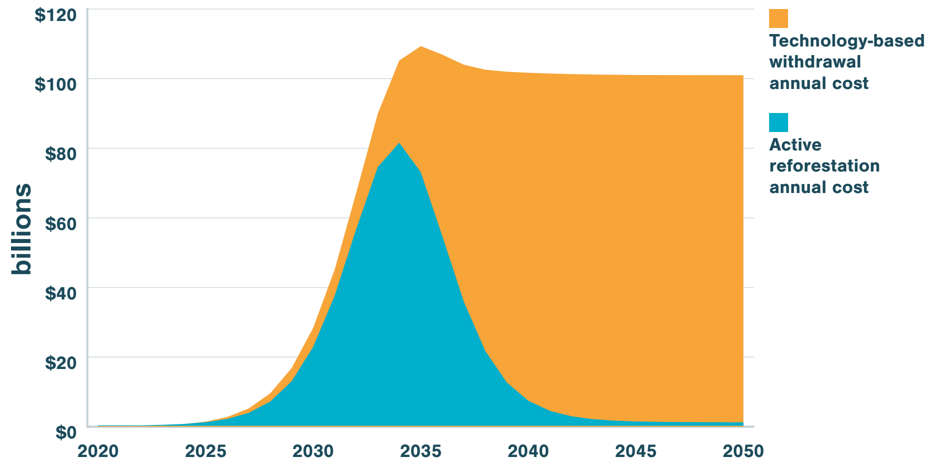


Source: RethinkX.

Carbon Withdrawal Cost

We estimate that the cost of carbon removal will fall to an average of under $10 per ton for both active reforestation and technology-based approaches by 2040. The total cost of carbon withdrawal is initially dominated by active reforestation, but later gives way to technology-based approaches that can be sustained indefinitely as needed (we assume at a total annual cost of roughly $100 billion, as shown in Figure 28).

Figure 28: Annual Carbon Withdrawal Cost – 'Get Serious' Scenario



Source: RethinkX.

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Notes

a These forecasting derivatives, meaning the way in which forecasts themselves are changing, are very revealing metrics that conventional analyses seldom if ever address.

b We were unable to find reliable estimates for pre-industrial marine biomass or the rate of recovery to that baseline in the event that commercial fisheries were to cease. Such estimates appear to be entirely absent from the scientific literature, and our discussions with established oceanography and marine biology experts confirmed that this is a notable knowledge gap. However, based on other known aspects of the planetary carbon cycle, we can infer that sequestration of carbon in marine biomass after the food disruption wipes out commercial fisheries will not be a significant source of carbon withdrawal relative to either reforestation or other technology-based mechanisms.

c This median 2°C pathway conforms to the IPCC "Lower-2°C" pathway class that limits peak warming to below 2°C during the entire 21st Century with greater than 66% likelihood.[12]

d History has shown that the climate forecasting derivative, meaning the way in which forecasts themselves are changing, has almost always moved in the direction of 'worse'. So, although current research indicates that remaining below 2°C gives a 66% probability of averting the worst impacts of climate change, this assessment is only likely to change for the worse as new data are gathered and evaluated.[12]

e The rate of carbon withdrawal from passive reforestation varies over time, as well as by biome.

f The Jevons paradox, or Jevons effect, is a specific environmental example of a more general economic phenomenon known as a rebound effect which results from a disproportionately large increase in consumption associated with a decrease in price due to high price elasticity of demand. The concept of price elasticity of demand was discovered by Alfred Marshall in 1890, and thus did not yet exist in 1865 when William Stanley Jevons first noticed the rebound effect in energy (coal) technologies. The Jevons effect is real, but not inevitable. For example, digital cameras (and now smartphones) did not create a Jevons effect for celluloid film, despite triggering a million-fold increase in photograph production and consumption. Instead, digital cameras closed the celluloid film loop and disrupted the old technology entirely. Similarly, automobiles did not create a Jevons effect for horse manure, despite triggering a thousand-old increase in vehicle miles travelled. Digital cameras and automobiles have their own environmental impacts, but these in turn can and will be obviated over time as new disruptions occur and technology continues to advance.

Adam Dorr

Adam Dorr is an environmental social scientist and technology theorist whose current research with RethinkX is focused on the disruption of the global energy sector by new energy generation and storage technologies, and its intersection with similar disruptions set to unfold across the economy. He completed his MS at the University of Michigan's School for the Environment and Sustainability and his PhD at UCLA's Luskin School of Public Affairs, where he studied the environmental politics, policy, and planning around disruptive technologies. He has a decade of teaching, lecturing, and presenting experience.

Tony Seba

Tony Seba is a world-renowned thought leader, author, speaker, educator, angel investor and Silicon Valley entrepreneur. He is the author of the #1 Amazon best-selling book "Clean Disruption of Energy and Transportation", "Solar Trillions" and "Winners Take All", and co-author of "Rethinking Transportation 2020-2030", "Rethinking Food and Agriculture 2020-2030", and "Rethinking Humanity".

He has been featured in several movies and documentaries including Bloomberg's Forward Thinking: A Sustainable World, 2040, and SunGanges. He is recipient of many awards including the Savvy Awards (2019), Solar Future Today's Visionary Influencer Award (2018), and Clean Energy Action's 2017 Sunshine Award. He is the creator of the Seba Technology Disruption Framework™. His work focuses on technology disruption, the convergence of technologies, business model innovation, and product innovation that is leading to the disruption of the world's major industries. He has been a keynote speaker at hundreds of global events and organizations including Google, the European Commission, Davos, COP21, CLSA, J.P. Morgan, Nomura, National Governors Association, Conference on World Affairs, the Global Leaders Forum, Intersolar and China EV100. He has taught thousands of entrepreneurs and corporate leaders at Stanford Continuing Studies. He has a Stanford MBA and an MIT degree in Computer Science and Engineering.

James Arbib

James Arbib is chairman of a UK-based family investment office with a diversified portfolio across all asset classes and a focus on the risks and opportunities of technology disruption. He is the founder of Tellus Mater, an independent philanthropic foundation dedicated to exploring the impacts of technology and its potential for solving some of the world's most challenging problems.

He is the co-founder of RethinkX and has given keynote speeches at dozens of events including for BlackRock, Goldman Sachs, governments and corporations.

A graduate in history from Trinity College, Cambridge, he has a Masters in Sustainability Leadership, also from Cambridge. He is a qualified chartered accountant and worked as an investment analyst covering utilities.

The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

Rethinking Climate Change

Technology disruptions already underway in the energy, transportation, and food sectors have extraordinary implications for climate change. These three disruptions alone driven by just eight technologies can directly eliminate over 90% of net greenhouse gas (GHG) emissions worldwide within 15 years. Market forces can be leveraged to drive the bulk of global GHG emissions mitigation because the technologies required are either already commercially available and competitive today, or can be deployed to market before 2025 with the right societal choices. The same technologies will also make the cost of carbon withdrawal affordable, meaning that moonshot breakthrough technologies are not required to solve the 'Last Carbon Problem' and go beyond net zero from 2035 onwards.

Our previous research has shown that disruptions of the energy, transportation, and food sectors are inevitable. Solar, wind, and batteries (SWB) will disrupt coal, oil, and gas. Autonomous electric vehicles (A-EVs) providing transportation-as-a-service (TaaS) will disrupt internal combustion engines and private vehicle ownership. And precision fermentation and cellular agriculture (PFCA) will disrupt meat, milk, and other animal products. The three disruptions are already unfolding simultaneously, and their implications for climate change are profound. Yet it will be up to us to decide whether or not we deploy these technologies worldwide rapidly enough to avoid dangerous climate change.