ToughTech

A publication by The Engine, built by MIT

FALL 2021

TRANSFORMATION 07

THE PANDEMIC, THE NEW U.S. ADMINISTRATION, AND THE RAPID DEVELOPMENT OF NEW TECHNOLOGIES PROVIDE US WITH AN OPPORTUNITY TO REDEFINE OUR FUTURE FROM THE GROUND UP. LET'S GET TO WORK.

pg.06

→ To successfully commercialize the kind of breakthrough, era-defining technologies that The Engine invests in, we need both the hammer of private enterprise, mobilized in highly efficient startup ventures, and the anvil of government support, backstopping the risk of those ventures and providing the necessary weight to persevere through obstacles.

→ Historians may well point to 2021 as a pivotal moment when hammer and anvil aligned in U.S. development of the key technologies of this century. Or not. Once the legislative door shuts, there is no guarantee that so much as a window will crack open.

→ It is time to renew that scale of government investment in order to commercialize the next round of technological innovations.

→ This is a unique and pivotal moment. Failure to act could leave the U.S. ceding the mantle of global innovation leader.

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→ From those primal days huddled around a fire for warmth or harnessing the power of the sun to preserve hides and food, humans and human evolution have been inextricably tied to the energy ecosystem.

→ It is important to reiterate that the fundamental source of carbon emissions is the carbon-heavy supply side of the current energy ecosystem. As a result, any CO_2-free energy system must either rely on carbon-free primary sources or mitigate CO_2 emissions from fossil-based primary sources.

→ The energy system of the future will involve the complex interplay of several solutions working together, taking the local context into account across four key classes of metrics spanning spatial, temporal, economic, and political factors.

THE ENGINE
Built by MIT

A home for Tough Tech founders.

The Engine, built by MIT, is a venture firm that invests in early-stage companies solving the world's biggest problems through the convergence of breakthrough science, engineering, and leadership. Our mission is to accelerate the path to market for Tough Tech companies by providing access to a unique combination of investment, infrastructure, and community.

Tough Tech 07

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THE ENGINE
Built by MIT

How can we shape the future?

As investors, scientists, engineers, and humans, it is that question that drives us to push forward, to get as smart as we can as quickly as we can so, with any luck, we can help make a difference.

This publication examines three industrial sectors — semiconductors, the built environment — and energy, and the critical role that they will play as the future of our planet unfolds. It examines these sectors at a unique point in U.S. history — we are amidst a global pandemic that has killed millions and wounded international supply chains, we have recently ushered in a new administration during a period of profound public skepticism and mistrust, we are witnessing a once-in-a-generation investment in technological infrastructure, and, above all, we are living surrounded by a climate in crisis, the effects of which will impact the fates of every living thing. To quote Margaret Atwood, "It's not climate change, it's everything change."

Yet we remain optimistic. We are in the privileged position to see our country's — and our globe's — best minds at work translating Tough Tech solutions into foundational companies. We watch as more public and private capital flows into these efforts than ever before. There is real opportunity to reshape some of our most complex industries for the better, an opportunity to make change on behalf of future generations.

The challenges ahead of us are massive, which is why it is so important, now more than ever, to understand the collection of people and systems that will help us solve them. This publication does not pretend to hold all of the answers. It does, however, showcase some of the people, technologies, and organizations doing their best work to find them. We hope it sparks meaningful conversation and that you will reach out with thoughts and ideas of your own.

KATIE RAE
CEO & Managing Partner
The Engine

HAMMER & ANVIL: DELIVERING ON THE POLICIES TO FORGE TOUGH TECH

BY *Rees Sweeney-Taylor*

TACTICIANS FROM ANTIQUITY to the present day have acknowledged the power of the "hammer and anvil": the agility of a highly mobile force — the hammer — works in sync with the solidity of a fixed position — the anvil — to overcome seemingly overwhelming opposition. To successfully commercialize the kind of breakthrough, era-defining technologies that The Engine invests in, we need both the hammer of private enterprise, mobilized in highly efficient startup ventures, and the anvil of government support, backstopping the risk of those ventures and providing the necessary weight to persevere through obstacles.

A confluence of factors opened the door in the summer of 2021 for the kind of government support that truly breakthrough technologies have often required. Over the past decade, a bipartisan consensus has emerged on the role of government in ensuring U.S. firms can compete on an equal footing with Chinese companies. November's elections gave the new president and Congress a strong mandate for more robust government investment in America's future. And a national reckoning with the devastating impact of the global COVID-19 pandemic — a low-likelihood but catastrophic event ultimately mitigated through public-private partnerships rapidly deploying advanced technology — changes how we view and prepare for risks in the decades ahead. But it remains to be seen whether lawmakers will use this opportunity to cross the open threshold and make the kinds of bold investments in Tough Tech needed to realize the full benefits here in the United States.

Historians may well point to 2021 as a pivotal moment when hammer and anvil aligned in U.S. development of the key technologies of this century. Or not. Once the legislative door shuts, there is no guarantee that so much as a window will crack open.

As we note in *A National Frontier Tech Public-Private Partnership to Spur Economic Growth*, due to persistent market failures government investment is necessary at multiple points along a technology's development. While private capital markets are strong and U.S. academic labs continue to lead the world in technology development, our global competitiveness in critical fields of innovation continues to fall behind. Numerous challenges exist on the arduous journey from initial lab breakthrough to successful commercialization, a journey known as the Valley of Death.

Markets are ill-designed to meet some of these challenges. Private investment in Tough Tech lags because of its greater time to maturation, which is misaligned with return expectations of private capital. Regulatory constraints, designed for incumbent technologies, increase hurdles for startup firms. As we propose in *A Foundational Technology Development and Deployment Office*, the government has a critical role to play in fostering a healthy ecosystem for these innovative companies to succeed.

In June 2021, in a rare bipartisan moment, the Senate passed the U.S. Innovation and Competition Act (USICA), funding the CHIPS program with $52 billion for semiconductor research, design, and manufacturing, and authorizing significant budget increases at the National Science Foundation, the Department of Energy, and the Department of Defense for R&D in ten key technology areas: artificial intelligence, semiconductors, quantum computing, robotics, disaster prevention, communications, biotechnology, data storage, energy, and materials. NASA's Human Lander System, which will return humans to the Moon, also saw an increased authorization. And the bill creates regional technology hubs, developed by the Department of Commerce, which will geographically distribute the wealth creation of research and enterprise.

As of Congress's August 2021 recess, differing versions of the bill have passed the House and Senate; the two bodies must iron out the discrepancies between the two versions before sending a final bill to the White House, which has expressed its support.

All of this is an excellent start and a remarkable achievement in an age marked by partisan bickering. However, passage of USICA is only the beginning. For decades, government's role has been constrained; U.S. government R&D spending has dropped from highs in the 1960's of 2% of GDP to less than 0.7%. As we explore in *Building a 21st Century Economy*, large-scale government investments in previous decades contributed to the creation and development of industry-defining technological breakthroughs such as the Internet, GPS, semiconductors, and the Human Genome Project. It is time to renew that scale of government investment in order to commercialize the next round of technological innovations.

Indeed, large-scale partnerships are not only the stuff of Cold War-era government investments. NASA's Commercial Orbital Transportation Services (COTS) Program, which was established in 2006, successfully leveraged $500 million in government funds to encourage private industry to develop the transportation capabilities to meet the needs of the International Space Station. Again, this was an excellent start, but many more such public-private partnerships are needed to retain our innovative edge and solve the most pressing problems of our time, yielding advances in such areas as fusion energy and next-generation semiconductors.

Historians may well point to 2021 as a pivotal moment when hammer and anvil aligned in U.S. development of the key technologies of this century.

Strategic government investment in the key technology areas listed above would provide a powerful boost to the economy. A September 2020 study by PwC, *Impacts of Federal R&D Investment on the U.S. Economy*, suggests that Tough Tech industries could support the creation of over 3.4 million U.S. jobs and $478 billion in annual economic growth this decade, in some cases establishing entirely new industries such as:

+ Next-generation semiconductors that will provide the backbone for a broad range of industries like autonomous vehicles, smart cities, and telemedicine.
+ Energy technologies such as fusion, geothermal, and energy storage that will help mitigate the climate crisis.
+ Quantum computing that will exponentially expand computing power, potentially solving problems including encryption and cryptography, molecular modeling, and autonomous vehicle simulations.
+ Synthetic biology that could cure previously incurable diseases, radically expand the food supply to feed a planet of 10 billion people, and make previously scarce resources more available.

This is a unique and pivotal moment. Failure to act could leave the United States ceding the mantle of global innovation leader. Such a loss may prove irreversible as Chinese dominance of 5G technologies and next generation semiconductors would define new industry standards, making U.S. companies reliant on their Chinese counterparts and derailing U.S. attempts to catch up. In the United States, entrepreneurs and policymakers have always relied on one another for the hammer and anvil that are required to forge Tough Tech marvels; this moment is no different, and we need the right policy solutions to make that partnership possible.

POLICY & PROGRESS

Addressing the world's toughest challenges is a complex systems problem, and private capital is just one piece of the solution. Realizing the full impact of Tough Tech innovation requires public and private collaboration to go from breakthrough technology to commercialization to ethical, widespread impact on our economies and societies.

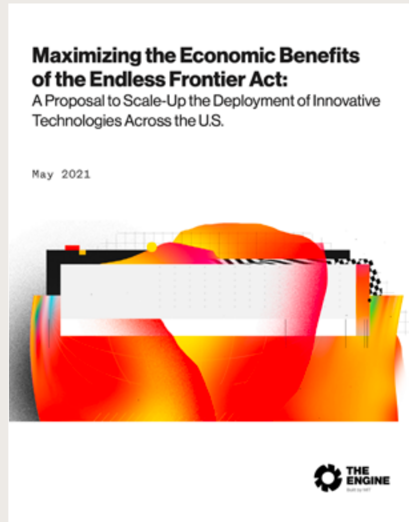
Building a 21st-century Economy: The Role of Tough Tech in Ensuring Shared, Sustainable Prosperity

PUBLISHED NOVEMBER 2020

"Tough Tech holds the promise of creating entirely new industries as well as revitalizing historically foundational sectors such as steel, energy, and manufacturing that are under global competitive strain to shutter or offshore. But Tough Tech alone cannot provide this future. The combination of these breakthrough technologies with the right government and private sector interventions holds the potential to impact the challenges that unite us globally. Ensuring the inclusion of all the diverse stakeholders in the development and application of these technologies is critical to realizing the positive impacts to social equity and shared economic growth. The U.S. must act now with a sense of urgency to protect and expand these middle-class jobs across the U.S. while also ensuring continued U.S. global leadership in the 21st-century economy."

Maximizing the Economic Benefits of the Endless Frontier Act

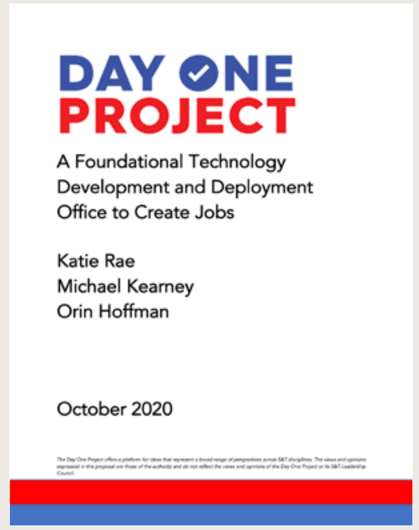
PUBLISHED MAY 2021



"The U.S. is hamstrung today because technology pilots, scale-up, and commercial demonstration lack sufficient private sector support. … The federal government should help fill this gap by creating a new, centralized agency to run deployment grant and loan programs within the Department of Commerce. This funding would complement the Endless Frontiers Act authorizations for regional technology hubs as deployment of technology fundamentally engages workers with different skills than those utilized in R&D alone."

A Foundational Technology Development and Deployment Office to Create Jobs

PUBLISHED OCTOBER 2020



"The history of the United States is replete with examples of how foundational new technologies can transform the economy and create jobs. From the automobile to the transistor to recombinant DNA, foundational technologies have enabled an expanding middle class and prosperity for millions of Americans. The U.S. federal government has played a vital role in providing and enabling early market development and applications for these technologies. The United States must rededicate itself to promoting new technologies beyond the research and development phase if it is to maintain a position of global economic leadership and successful transition to the 21st-century economy."

National Tough Tech Public-Private Partnership to Spur Economic Growth

PUBLISHED OCTOBER 2020

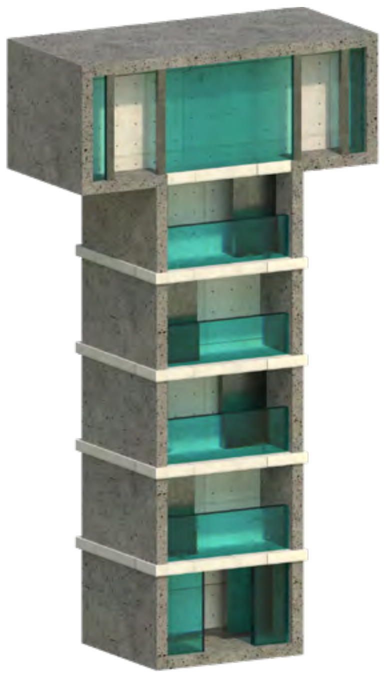
"Coupling government funding to private investment will push high-growth companies toward raising private capital, while also incentivizing private capital markets to open their investment apertures to higher-risk frontier tech companies. This is phenomenal leverage for taxpayer money, as small amounts of aligned government capital, in the early stages of company growth, will propel companies into the private capital markets. For example, if a $300k government matching grant can create initial private investment, these companies are now part of the venture capital growth trajectory. For many frontier tech companies, that can mean hundreds of millions of dollars of private capital throughout their growth stages that was spurred by a relatively small government investment."

THE GREAT REBUILD

Solving the planet's housing crisis while preserving our environment will require us to change what we build, how we build it, and what we build it with. It's an immense challenge. And here's how we can solve it.

BY *Monique Guimond, Chief of Staff at The Engine*

INTERVIEWS BY *Nathaniel Brewster & Monique Guimond* | ILLUSTRATIONS BY *Nicolás Carrasco & Andrés Rodríguez*



hink of the cities your grandchildren will inhabit and you might imagine something futuristic – driverless transit systems, sensor-packed buildings, augmented reality, and androids that cater to a city dweller's every need. But these cities will not be defined by the innovations that move, entertain, and comfort; rather, they will be defined by the innovations within – the stuff that buildings are made of and the way those buildings are put together. Because we are at a critical moment in time where the future of our built environment is in question, we must rethink how our most ubiquitous construction materials – cement, steel, glass, and wood – are made, transported, and assembled if we are to meet the world's vast need for housing while preserving the stability of the climate for subsequent generations.

Two of the primary challenges faced by the building industry are contradictory in nature. Buildings are some of the primary emitters of global greenhouse gases, and yet as the world's population grows and more industrialized economies emerge, we will need more, not fewer, of them to be built. One thing we do know is that continuing with current building and construction practices will almost certainly guarantee that the world will exceed the 2˚C warming limit above pre-industrial levels established by the Paris Agreement, regardless of any cuts other sectors are able to make. If this is truly the climate decade — where industries and governments come together to get our planet on track — it must also be the decade that our buildings are reimagined.

Change will be difficult. To create the cities of the future, the building sector — one of the world's largest and oldest — must undertake a transition rivaled only by the industrial revolution. We must not only change how we build but what we build with, and we must do so simultaneously.

Unlike some technology sectors that have a few players with massive worldwide market shares, the construction industry is highly fragmented and strictly driven by cost. There will also be regulatory and safety hurdles that differ by jurisdiction and long-established consumer bases requiring real cost incentives to shift processes or products.

But the opportunity is too immense to ignore. Global output of the construction industry is expected to grow to $15.5T by the end of this decade, and that pace will not taper. Buildings are and will continue to be central to human existence on this planet. They house us, provide places, employment, and for many are one of their most significant investments and sources of equity. Thankfully, technologies and frameworks to solve the industry's toughest challenges are emerging today. Now is the time to invest in bringing them to market — let's not miss it.

The Climate Challenge

Buildings are at the center of the climate crisis. We can say with confidence that the built environment accounts for 40%-50% of greenhouse gas (GHG) emissions annually, even though the exact share of emissions varies by source. At nearly half of global CO2 output, there is virtually no climate mitigation strategy that doesn't account for the built environment and its share of the problem.

The Intergovernmental Panel on Climate Change (IPCC), the body of the UN responsible for convenings such as COP21 (also known as the 2015 United Nations Climate Change Conference) that put forth the Paris Agreement of 2015, has said that the best chance at staying under the maximum threshold of 2˚C of warming over pre-industrial levels (let alone any shot at staying under 1.5˚C) will require eliminating all building sector emissions by the year 2050. That is a herculean order when projections also say we will need to build an additional two trillion square feet between now and then to sustain the world's needs. Such an effort is similar to adding more than 10 New York Cities (all five boroughs included) to the globe every year for the next 30 years.[1]

How exactly does the world tackle eliminating the emissions of every current and future building on the planet?

Most discussions centered on "green building" or "net zero" in the last few decades have focused on reducing the operational emissions of buildings — emissions produced by processes like heating, cooling, and lighting. This has translated to improvements like solar roof installations, smart heating and cooling systems, LED lighting, and highly insulated and tightly sealed buildings that trap more heat or cool air and thus require less energy for climate control. This is a crucial area for the sector to mitigate.

There is another, often overlooked area of built environment emissions, however, that Tough Tech breakthroughs are uniquely positioned to help solve. The *embodied* carbon of our built environment is everything that comes before a building goes into operation. Embodied carbon includes the energy and carbon emitted in the earliest stages of a building's life, from the extraction and manufacturing of materials to their transportation to site and, finally the construction of the structure itself.

Taken as a whole, the materials production, transport, and construction processes make up over 10% of global emissions (within the half that the building sector is responsible for). And for a building with an average lifespan of 80-100 years, embodied emissions will represent an average of 20% of total lifetime emissions.[2] This means that a fifth of a typical building's carbon footprint is already established before its doors even open. We must pay close attention to that 20% today. As operational emissions fall with successful industry initiatives, and with only 30 years to address the entire sector's emissions, the upfront embodied carbon of a building over those years constitutes a larger proportion of the overall sector emissions to be remediated.

LIFECYCLE EMISSIONS FOR A TYPICAL APARTMENT BUILDING

BUILDING OPERATION	70.43%
MATERIAL MANUFACTURING	18.87%
BUILDING DEMOLITION	5.63%
BUILDING DISPOSAL	2.91%
MATERIAL TRANSPORTATION	1.16%
BUILDING CONSTRUCTION	0.996%

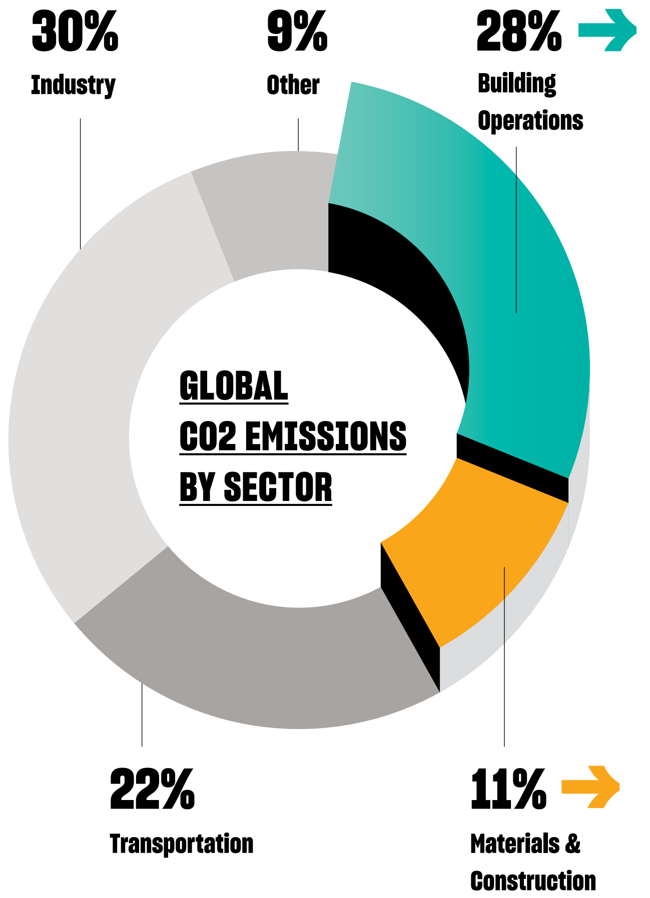
https://www.tandfonline.com/doi/full/10.1080/13467581.2020.1807989

1 Bruce King, *New Carbon Architecture: Building to Cool the Climate* (Gabriola Island, BC, Canada: New Society Publishers, 2018).
2 Bruce King, *New Carbon Architecture: Building to Cool the Climate* (Gabriola Island, BC, Canada: New Society Publishers, 2018).

THE EMISSIONS OF OUR BUILT WORLD

RESEARCH & CALCULATIONS BY CAITLYN MCCLOSKEY

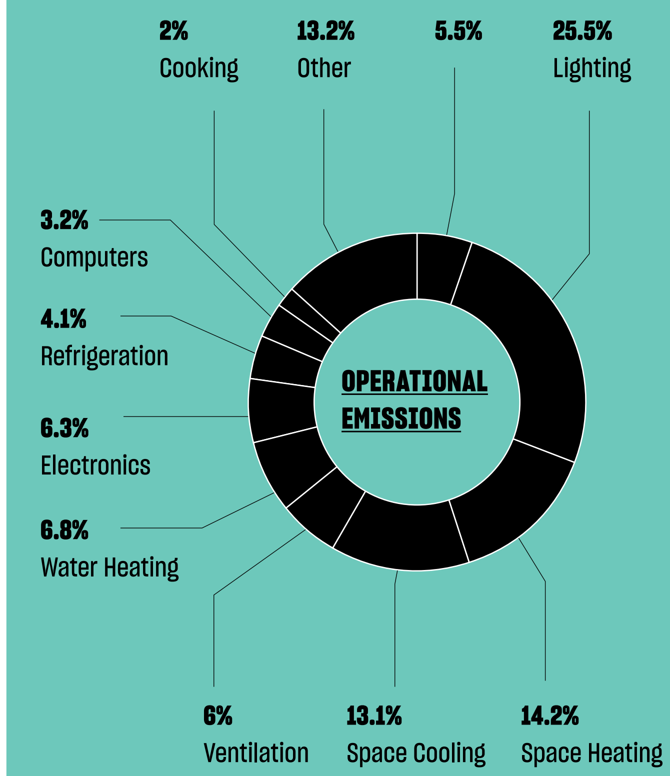
The graphic below shows the CO2 emissions from the built environment as percentages, with 11% due to the manufacture and production of building materials. Total global CO2 emissions are around 43 billion tons of CO2/year.



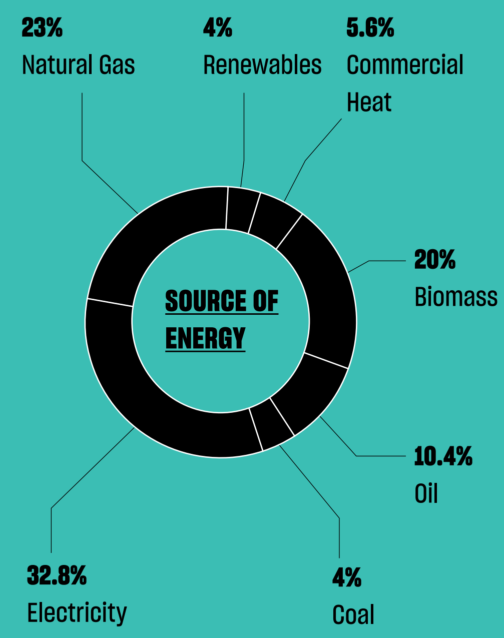
The data in this graphic is inherently variable. For example, some sources consider any form of transportation (basically anything coming out of an exhaust pipe) to be categorized even though some of that transportation likely involves the transportation of materials for the built environment.

We chose to use data from a 2017 report on the embodied carbon of buildings and infrastructure released by Forestry Innovation Investment to broadly categorize 80% of built environment emissions as originating from building operations, while the remaining 20% originate from embodied sources.

Operational Energy
Breakdown by end-use



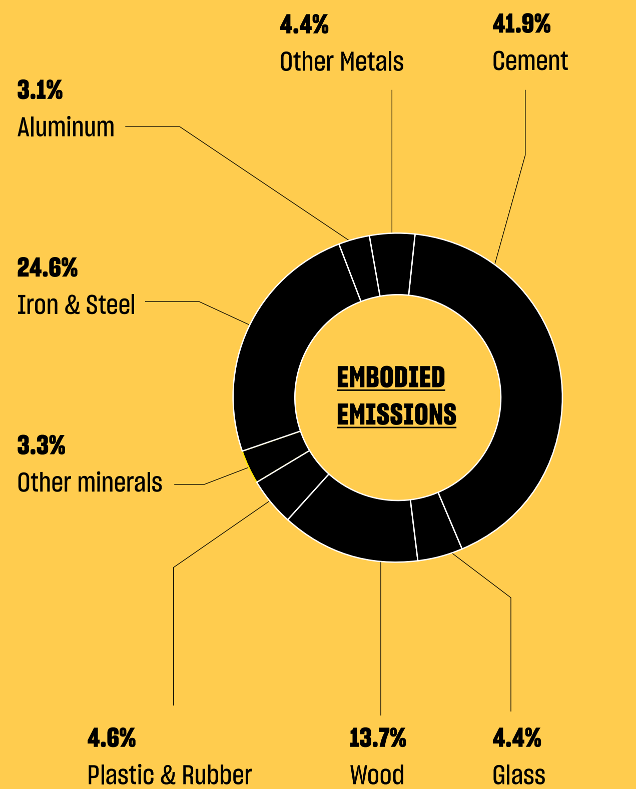
Operational Energy
Use by fuel type



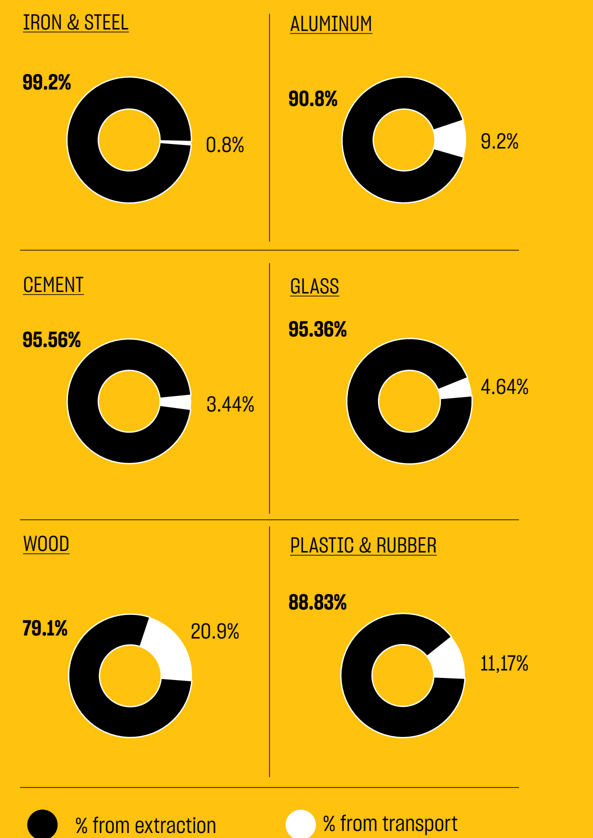
OPERATIONAL EMISSIONS

This data illustrates that the emissions from building operations can be viewed from three different perspectives: operational emissions broken down by different stages of the building's life, operational emissions broken down by the use of energy for systems and processes within the building, or operational emissions broken down by the production of energy for those uses. Technological advancements made from any of these perspectives can help cut emissions from the built environment as a whole. For example, an advancement that allows for a more efficient demolition process would cut 'built environment' emissions, as would the development of ultra-efficient lighting, as would the decarbonization of energy production.

Embodied Emissions
Breakdown by material



Extraction & Transportation Emissions
As a percentage of total embodied emissions by material



EMBODIED EMISSIONS

Just as operational emissions can be viewed from different lenses, embodied emissions can similarly be viewed from two perspectives: embodied emissions broken down by different stages of the building's life, or embodied emissions broken down by material. There is opportunity to reduce emissions in both cases; creating a more efficient method of material transportation would greatly reduce built environment emissions, as would a particular innovation in the production of steel. This data shows that the production, manufacture, and transport of cement in particular contributes enormously to the total embodied emissions of the built environment, highlighting the opportunity for advancements in that area.

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Boston Metal

This all creates extraordinary pressure to radically rethink the materials with and processes by which buildings are constructed, and to do so quickly. There is no pathway to meeting the world's goals on slowing climate change if we do not.

Steel and cement are arguably the two most significant emitters in the building sector and most widely used commodities worldwide, together accounting for roughly 15% of the planet's annual GHG emissions. Many are working to alter the processes by which these products are made, as well as the material properties themselves, in order to produce green cements and steels that could be commercialized at competitive prices.

Cement is quite literally the foundation upon which our built environment is constructed. The material emits roughly one ton of carbon for every ton produced — a staggering ratio — and, given its ubiquity, decarbonizing it is one of the largest hurdles for the construction industry. Any decarbonization efforts will require intervention in two areas: reducing the high temperatures needed to generate the binding clinker out of limestone, and limiting or capturing the carbon dioxide released when the limestone is reduced down to lime.

Sublime Systems, which is in The Engine's portfolio and led by electrochemist Leah Ellis and serial entrepreneur Yet-Ming Chiang, is working to tackle both of these decarbonization pathways. They are applying industrial electrochemical concepts to convert limestone into lime at room temperature, making the CO2 produced during the conversion process easier to capture and reducing overall energy consumption. Sublime's process can be powered by renewable electricity, in which case its operation is carbon-neutral.

Given the sheer scale of cement use globally, there are an encouraging number of groups working to tackle its emissions problem. Carboncure, Solidia, Carbicrete, and LC3 are just some of the startups around the world attempting to reduce the carbon output of the material, with industry incumbents like LafargeHolcim and CEMEX also providing low-carbon alternatives. Approaches include using recycled CO2 within the concrete mixture to store carbon and strengthen the solution (Carboncure, Carbicrete, and Solidia), or introducing low-cost and abundantly available clay, which emits very little carbon and reduces the amount of limestone that must be broken down (LC3).

Steel produces a similar amount of global carbon emissions each year, with the world is reliant on the material for nearly every building, infrastructure, and manufacturing project. Boston Metal's CEO Tadeu Carneiro, who is also in The Engine's portfolio, recognizes that steel will not be easily replaced, but he is working toward a future with no pollution from metals production. The company's unique Molten Oxide Electrolysis process merges innovations developed at MIT and best practices from the aluminum and steel industries. The technology uses an electrolytic cell that has three components: an anode, a cathode, and an electrolyte. The materials in these components allow ore to be separated into steel and oxygen with zero greenhouse gas emissions.

While steel and cement produce the greatest overall greenhouse gas emissions of all commonly used building materials, the production of aluminum, a metal used throughout the built environment, emits six times the amount of carbon than steel on a per-ton basis. Gypsum (which goes into drywall), standard insulations, glass, ceramics, carpet, and roofing all have emissions implications. The production of these materials, and the materials themselves, must also be reimagined to emit less CO2.

Cement is quite literally the foundation upon which our built environment has been constructed. The material emits roughly a ton of carbon for every ton produced — a staggering ratio — and, given its ubiquity, decarbonizing it is one of the largest hurdles for the construction industry.

↙ Boston Metal pouring a green steel ingot at its Woburn, MA headquarters. *Photo: Boston Metal*

↘ The Mjøstårnet in Brumunddal, Norway, the world's tallest timber building. *Photo: Voll Arkitekter, http://vollark.no/portfolio_page/mjostarnet/*

Alternative methods to cut the embodied carbon of a building include increasing the use of existing and improved regenerative materials like timber, bamboo, or straw, that actively store and remove carbon from the atmosphere. Though timber is of course a widely used material in construction, its structural use beyond several-story dwellings has been limited.

The primary challenges with regenerative materials are twofold; first, their structural integrity limits building the multi-story infrastructure needed for most urban settings; second, production is at the mercy of natural growth cycles. Traditional construction woods like fir, hemlock, and pine can take decades to grow and mill. Other materials such as bamboo can be cultivated in much shorter cycles than timber, typically in fewer than 10 years. Bamboo, however, has different structural properties than woods that make its widespread use as a building material less likely.

The rise of cross-laminated timber (CLT) shows us how a manufactured timber-based product can replace steel, perhaps altogether. The CLT production process binds the grains of wood in perpendicular layers, enhancing their structural capacity and allowing for larger dimensions, typically around 40 feet, though some cases have been even longer.[3] CLT panels can reduce the carbon footprint of a building by replacing walls, floors, and structural components, creating a true carbon sink that offsets emissions for generations.

In some projects, engineered timber has fully replaced steel. Completed in 2019, the 18-story Mjøstårnet in Norway is the world's tallest all-timber building.

Widescale adoption of such materials faces significant hurdles like building code adoption, which currently limits the number of stories a developer can build with the material, and cost, which remains high in comparison to incumbent materials such as steel and concrete.

There are also emerging innovations with wood at the molecular level. Inventwood, spun out of the University of Maryland, is pioneering methods to compress and chemically treat wood fibers to make it stronger than steel while still significantly lighter and carbon negative. The startup is also modifying lignin and hemicellulose to create translucent material that could someday replace windows or insulation in buildings.[4] These innovations imagine a world where regenerative timber products could become a larger component in the construction of urban high rises and developments, cutting back on the use and emissions of non-regenerative materials and the need to manufacture and transport large-scale panels such as CLT.

It should also be noted that new methods of integrating more timber into our built environment at massive scale are not emissions free. Wood extraction and the milling and production of timber for construction, whether in new or traditional forms, can also emit carbon. We must work to produce a material that still stores more carbon than it emits in the process, and this is possible given the right forestry, production, and treatment processes.

3 https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt
4 https://www.newscientist.com/article/2163306-eco-friendly-nanowood-is-a-super-strong-and-recyclable-styrofoam/

We must work to produce a material that still stores more carbon than it emits in the process, and this is possible given the right forestry, production, and treatment processes.

What some are calling a "living architecture movement" is also gaining momentum. This field uses synthetic biology to grow structural materials for building construction. Researchers have tested the use of algae, fungi, and bacteria to grow bricks and cements organically and repair cracks or damage in existing structures and materials. The Living Materials Laboratory at the University of Colorado Boulder, for example, is experimenting with e.coli to produce styrofoams and limestone products as well as cyanobacteria (plant-based microorganisms) to create living cement bricks.

Startups like Ecovative Design are harnessing the self-growing properties of fungi or mycelium to create structural composites that could be integrated into a building.[5] And other living cells could be used to conduct electricity through biofilms or as bio photovoltaics that introduce regenerative materials into solar capture, possibly for use as a material on entire building envelopes. The B.I.Q. house completed in 2013 in Hamburg, Germany as a result of a competition used an algae facade to capture solar energy to power the building.

Though in the early stages and like something out of science fiction, these are the types of developments that could transform the impact of our buildings, if we can find ways to commercialize them at scale. The potential of self-powering, self-growing, and self-repairing properties have already caught the attention of DARPA and NASA, for example, for the long-term possibilities of having genetically engineered buildings in remote settings.[6]

The weight and density of our buildings and cities also have profound implications for the sector's role in climate change. The reasoning is quite simple: with denser and heavier materials, more finite resources must be used to create them, producing greater emissions in the process. Adding to this are the inherent emissions from transportation, which typically increase in response to the material weight.

Reducing material density while maintaining structural integrity, and developing methods for more decentralized or localized production of materials, could significantly improve that problem. Electrifying transportation will help cut emissions from the movement of materials, but that transition relies on abundant renewable sources of energy, will take decades that we don't necessarily have, and will likely impact commercial freight (the modes moving heavy materials) after all other modes of transportation. We should be looking for lighter-weight solutions that can be integrated into building processes today.

Graphene is a carbon material that has 5% the density of steel but 200x its strength, along with superconducting properties. First produced in 2004, engineers are still discovering new potential applications. Graphene can be used to add structural properties to existing building materials and has the potential to someday be used as a 3D building material itself.[7] Currently, due to its prohibitive cost, graphene applications in the construction industry mostly include supplementing existing materials such as paint or cement to make them more durable and water or rust resistant. Such applications require less structural mass in materials during build and maintenance cycles, but its properties don't yet scale to replacing the core components of a building altogether.

5 https://www.pbs.org/newshour/science/new-research-is-finding-ways-to-turn-living-cells-into-mini-factories-for-materials
6 https://www.forbes.com/sites/johncumbers/2019/09/26/can-we-redesign-the-modern-city-with-synthetic-biology-could-we-grow-our-houses-instead-of-building-them/?sh=23d67883299b
7 ttps://science.howstuffworks.com/innovation/new-inventions/graphene.htm

MATERIAL CAUSE

Estimates of carbon emissions for a 20-story (30,000 m^2) apartment building.

RESEARCH & CALCULATIONS BY CAITLYN MCCLOSKEY

We acknowledge that buildings are as diverse as the communities in which they are built. For the sake of these estimates, we chose to analyze a typical 20-story apartment building of the kind found in urban areas across the globe. These buildings are composed of traditional materials like steel, cement, glass, and gypsum and provide a relevant lens through which to examine the emissions impact of those materials. These estimates also account for mechanical, electrical, and plumbing (MEP) systems. We do not include furniture in this analysis.

MATERIALS	% OF TOTAL MATERIALS	% OF TOTAL EMBODIED EMISSIONS	% OF BUILDING'S TOTAL LIFETIME EMISSIONS (INCLUDING EMBODIED & OPERATIONAL)
↳ STEEL A > 1,000,000 B > 1,700,000 C > 13,600	11.5%	16.7%	3.340%
↳ CEMENT A > 6,000,000 B > 5,700,000 C > 196,080	69.3%	56.0%	11.198%
↳ GLASS A > 230,000 B > 207,000 C > 9,605	2.7%	2.0%	0.407%
↳ GYPSUM A > 400,000 B > 288,800 C > 130,884	4.6%	2.8%	0.567%
↳ WOOD A > 83,000 B > 33,200 C > 6,939	1.0%	0.3%	0.65%
↳ ALUMINUM A > 133,000 B > 1,596,000 C > 146,832	1.5%	15.7%	3.136%
↳ CERAMICS A > 150,000 B > 30,000 C > 5,040	1.7%	0.3%	0.59%
↳ PLASTIC A > 150,000 B > 76,050 C > 8,366	1.7%	0.7%	0.149%
↳ COPPER A > 16,307 B > 48,921 C > 2,446	0.2%	0.5%	0.096%

A > Amount in typical 20 story-building (kg)
B > Total embodied carbon emissions from materials (manufacturing, extraction, transportation in kg CO2)
C > Carbon emissions from transportation of material (kg CO2)

Carbon nanotube composites, a cousin of graphene but containing other elements like oxygen and nitrogen, have existed for decades as components of airplanes, boats, wind turbines and other high-performance vehicles and structures. With the ability to custom tune strength and weight ratios, they are becoming an increasingly viable alternative to traditional materials as advancements continue to drive the cost of production down.[8] Carbon composites can be used to produce moldable unitary, jointless parts, which could reduce time, materials, and overall costs in the construction process, and with a low density could also reduce transportation costs and emissions.

These composites are made by transforming gas into solid materials in which carbon is stored, versus burned into the atmosphere. The material could present an environmentally friendly solution to transitioning the oil and gas sector. New developments in methane pyrolysis are also working to split off hydrogen from solid carbon, creating a clean fuel and structural material in one process.

Recent discoveries out of Rice University have shown how carbon materials can be produced from carbon dioxide emitted from food and waste which could introduce graphene into the carbon capture category that helps to mitigate the implications of our existing trades.[9] Other researchers within the U.S. Forest Service as well as Mississippi State University have been working on ways to produce graphene using lignin, a byproduct of the pulp and paper industry, eliminating the need for petroleum based products altogether.[10]

While perhaps ironic, it is possible that the oil and gas industry could supply an economically viable and sustainable solution to the world's building needs.

The Housing Challenge

While it is clear that building more volume comes with significant risk to the planet, slowing down the pace of construction is not an option. Instead, the globe will need to accelerate its housing output in order to match the demands of its growing population, which is expected to grow by 2.5 billion in the next 30 years.[11] Trends in better standards of living as emerging economies develop and a reduction in family sizes and birthrates mean that this population growth will come with proportionally more households, requiring even more material resources than the growth that came before.

Some developed nations have shown us what this could look like already; for example, the National Records for Scotland show a household demand vs. population growth discrepancy of 7%-8%. If you apply that same discrepancy to the entire planet, we would have to construct two billion homes by 2100 (800 million more than population growth alone is expected to require).[12] Our current practices will not be able to meet that rising demand. In fact, analysts identified a $1.6T productivity gap in 2017 for the building sector, an industry that comes in second to last for sector-wide digitization (after agriculture). This productivity lag is exemplified across the world with most countries having large and growing housing gaps. Looking to the State of California as an example, it would need to construct 3.5M housing units by 2025 in order to eliminate its own shortage. But as a whole, construction productivity is not merely struggling to keep up, it is slowing down, with the productivity of construction declining by 10%-20% in the past 20 years.[13]

Buildings also account for an unsustainable amount of resources, many of which are wasted on-site before even making it into the finished product or discarded at the end of a building's life, as the vast majority of our buildings are not constructed with their own deconstruction in mind. Demolition of a building often renders any efforts to recycle materials nearly impossible, yet the construction industry accounts for 60% of the world's resource consumption, most of which has a finite limit to their supply.[14] For example, there is more copper in our built environment than in the earth's crust. Half of worldwide mass waste comes from the sector, and typical sites will scrap between 10%-30% of materials before a project is done.[15]

How we introduce more efficient practices that accelerate our construction processes in a cost-effective way while cutting down on the amount of materials needed or wasted in the process will determine the standard of living our built environment is able to provide for generations to come.

8 https://www.innovativecomposite.com/what-is-carbon-fiber/
9 https://news.rice.edu/2020/01/27/rice-lab-turns-trash-into-valuable-graphene-in-a-flash/
10 https://www.usda.gov/media/blog/2018/03/16/wood-product-stronger-steel-could-change-world
11 https://www.sustainablehealthycities.org/research/weight-cities-resource-requirements-future-urbanization
12 https://theconversation.com/the-world-needs-to-build-more-than-two-billion-new-homes-over-the-next-80-years-91794
13 https://www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products#
14 https://www.sustainablehealthycities.org/research/weight-cities-resource-requirements-future-urbanization
15 Ilka Ruby and Andreas Ruby, *The Materials Book* (Berlin: Ruby Press, 2020).

Integrated Solutions

Developments in advanced robotics and offsite or modular construction show how the sector could begin to see a paradigm shift in productivity and the ability to satisfy the world's demand for housing.

Modular construction introduces full or partial manufacturing and assembly off-site, typically in nearby facilities; installation then takes place in a fraction of the typical time. The use of precision robotics and off-site planning can also significantly reduce material waste, with fewer errors on the job and the ability to reuse materials for other projects being assembled within the factory. This practice has gained popularity in regions with significant labor shortages and climates that have short windows for building due to harsh seasons or limited daylight hours, such as the Nordic region of Europe.

A recent McKinsey report featuring modular and prefabricated building practices outlined a vision for cutting schedules by 20%-50%, overall costs by 20%, and waste to a significant degree.[16] These cuts could move the needle for developers, allowing additional units to come online more quickly and accelerating the speed and productivity of the building sector as a whole.

How we introduce more efficient practices that accelerate our construction processes in a cost-effective way while cutting down on the amount of materials needed or wasted in the process will determine the standard of living our built environment is able to provide for generations to come.

16 https://www.mckinsey.com/business-functions/operations/our-insights/modular-construction-from-projects-to-products#

↖ Fabrication of Building Components at WoHo Lab in Madrid.
Photo: WoHo Systems

↗
A recently completed WoHo pilot project.
Photo: WoHo Systems

WoHo Systems, a startup funded by The Engine and founded by real estate veteran Israel Ruiz and architects Débora Mesa and Antón García-Abril, is working to improve on these projections of time and cost savings while delivering modular buildings that reduce the ecological footprint of buildings by 70%. They aim to do all this while enhancing project predictability and construction quality that will enable their modules to construct high rise buildings, which has remained a challenge for off-site industrialized construction to date.

The company has developed a system of discrete foundational components which can be scaled and configured to span both residential and commercial buildings like multifamily housing, hotels, labs, offices, and dormitories. This approach gives WoHo control over the design, material selection, and overall quality of each assembly at a finer level than traditional construction, allowing the team to continuously iterate and improve facets of their assemblies without stalling production.

But the construction industry is not a "winner-take-all" market, and there are multiple groups using new approaches to accelerating the build process. Prescient, for example, is streamlining digital design-build structural systems that can be robotically assembled on-site in a fraction of the time with extreme tolerances. Others like Juno and Factory OS are working to introduce affordable and sustainable options that deliver more housing more quickly, and IKEA and Skanska have partnered to bring BoKlok to the European market.

The recent shuttering of modular timber startup Katerra, which attracted over $2 billion in venture financing from Softbank and others, raised questions about the viability of this practice at scale. Without speculating on its ending, however, it does underscore the need to work closely with regulatory and industry partners as these new practices are introduced into the market.

As regulatory bodies and ecosystem players begin to adopt the practice, even more efficiencies will be unlocked. Ruiz described a future for the building industry similar to that of automotive assembly lines, noting that with quality control standards in place, eventually builders won't have to rely on on-site inspections on a unit-by-unit basis, significantly speeding up the rate of production. Despite some hurdles and setbacks, the global market for modular construction is still expected to reach $115 billion by 2028.[17]

Our Buildings Reimagined

This report is on the challenges that Tough Tech, in particular, will need to solve within the production and construction phases of our built environment, but many more issues loom. How will we deal with the refrigeration and cooling of our buildings — one of the biggest offenders to the environment — which will only grow in use as global temperatures rise? How will the sector ensure that the labor is not displaced as we look for more efficient ways to build faster and with less waste? What interim steps can we take now while some of the most advanced innovations get to market?

What interim steps can we take now while some of the most advanced innovations get to market? Achieving zero-carbon steel and cement could be a holy grail to the construction industry, but as Greg Smithies from Fifth Wall Ventures described, there are actions we can take now that can help mitigate significant emissions while those technologies mature. Replacing coal furnaces with hydrogen in material production facilities could offset carbon within those processes by 40%, for example.

And how will the public sector play a role in encouraging a necessary shift in the way we build? We can't wait for or rely on policy to subsidize an entire transition, making new products and solutions competitive across the board, but there are critical steps that should be taken to help push the industry in the right direction. Our governments can fund R&D and scaling building technologies, introduce disincentives-for excessive waste, and provide the industry with incentives for shifting toward greener and more efficient practices that cut emissions while housing more people affordably.

Transitioning our building sector to meet the world's rising housing demands without perpetuating the climate crisis is one of the toughest challenges technology and society has ever faced. While emerging technical solutions hold promise, they will need the support of additional capital — both private and public. The same attention that is focused on electrifying our transportation sector should also be directed toward decarbonizing the buildings we inhabit every day — and ensuring we can scale such innovation to every corner of the world. +

ISRAEL RUIZ
CEO & Co-Founder, WoHo

DÉBORA MESA
President & Co-Founder, WoHo

ANTÓN GARCÍA-ABRIL
Executive Chairman & Co-Founder, WoHo

GREG SMITHIES
Partner, Climate Technology Investment Team, Fifth Wall

17 https://www.fastcompany.com/90643381/this-prefab-builder-raised-more-than-2-billion-why-did-it-crash

Interview

BEN THOMPSON

Director of Sustainable Business | Autodesk

What excites you most about the construction industry today? A material? A process? A philosophy?

I'm excited about all the above, particularly the promise of new end-to-end technologies and their ability to enable project teams to address longstanding issues in the construction industry. Today, we're seeing more adoption of digital tools that connect and coordinate stakeholders and processes from the job site to the trailer and back to the home office. This greater alignment can reduce project carbon emissions, time, cost, and waste. It can even make it easier to adopt more modular approaches to construction and compound these savings. The technology available today allows for easier and more accurate accounting of both operational and embodied carbon during design and construction, so we can collectively tackle a significant source of global greenhouse gas emissions.

Second, I'm inspired by what our customers set out to achieve. For example, Norconsult is a construction engineering consultancy that is leading an ambitious highway expansion project in western Norway with rigorous low-carbon targets. So far, they've enabled a 15% reduction of CO_2 emissions for the Trysfjord bridge alone by reducing concrete usage, and they're set to reduce emissions associated with overall construction by 20%.

How do you reconcile the competing challenges the built environment faces — that we need more housing quickly and that such housing, if we are to keep the worst of climate change at bay, needs to be holistically carbon neutral? That of course normally comes at a cost premium.

Up to 30% of construction activity on-site is related to rework, and as much as 30% of construction material is wasted on-site, costing time, money, resources, and greenhouse gas emissions. Better coordination across the design, construction, and operation of the built environment with digital tools can significantly reduce this rework and the resulting emissions, also saving on project cost and time. This transformation toward more streamlined and environmentally friendly housing is achievable through the deployment of digital tools that give the industry actionable information, automated processes, and better coordination.

The key is not only to build more but also institute processes that are inherently sustainable over the long term and leverage the right technology to help us get there. We work with several startups and nonprofits innovating in this space. Here are a few examples:

BamCore is a next-generation building technology company that manufactures bamboo-based structural building components that speed construction and shrink a building's carbon footprint. BamCore builds prefab wall packages from timber bamboo, which is stronger, faster-growing, and sequesters more carbon than other wood. The BamCore Prime Wall System is two times stronger and up to 60% more thermally efficient than conventional stud-framed walls. Plus, the timber bamboo used in the panel sequesters five to ten times more carbon dioxide than wood.

MultiGreen is a real estate development and operating company that plans to build 40,000 economically and environmentally sustainable tech-enabled housing units by 2030 in the United States. They use Autodesk technology to digitize and connect their processes, data, and teams across all phases of the initiative, from design to operations, and the company plans to deploy green building principles across the entire project lifecycle.

Build Change helps developing communities ravaged by earthquakes and typhoons reconstruct, retrofit, and resist future damage. With support from the Autodesk Foundation, Build Change designs earthquake-resistant houses for developing countries and trains builders, homeowners, engineers, and government officials to build them.

Who will be the first player in the construction ecosystem to make the leap to carbon-neutral or zero-carbon processes at an industrial level? And how will such a shift affect the other players in the ecosystem?

An example that immediately comes to mind is The Kendeda Building on the Georgia Tech campus. The structure was built by Skanska USA to be a "Living Building", and it's one of the most environmentally advanced buildings in the Southeast. Using digital 3D modeling and simulation and analysis, their teams could compare multiple options and approaches and balance all the possible costs — not just financial, but environmental and for the community. Its solar panels produce extra electricity for the grid, its cistern collects and purifies rainwater; and it has a rooftop garden for food for students and faculty. We're hoping to see this process replicated elsewhere.

Which facet of the built environment faces the largest hurdle to decarbonize? Why is this? And who is proposing the most intriguing solutions?

Construction is still often a very adhoc process, especially in residential projects and some geographies. Even the most sustainably designed buildings could then have less sustainable build processes. As the grid decarbonizes, process and embodied emissions become a lot more important and are often challenging to address because they can require systemic changes to projects and even the broader industry.

The key here is learning lessons from the manufacturing sector to industrialize and digitize construction. Connecting this process to design digitally can lead to high levels of off-site and modular construction, which not only improve delivery efficiency but also offer higher levels of operational efficiency when the building is occupied.

Some construction firms are making sustainability a priority, but the information is siloed, technologies are not yet widely adopted, and the workforce doesn't have the skills needed to drive these outcomes industry-wide. Giving designers, contractors, and owners data to streamline these approaches AND make more sustainable choices across the project lifecycle from initial concept to operation is starting to help decarbonize the sector.

One company at the forefront of innovation is the construction start-up Factory_OS. They've cracked the code to improve productivity and efficiency by constructing modular units on an assembly line in a controlled factory setting to send on-site to make multi-family buildings. Autodesk and Factory_OS have been working together for several years to improve the overall outcomes of construction in an effort to promote social good. Now, with design and engineering under the same roof, Factory_OS offers more effective collaboration and issue resolution.

What is the most unexpected source of greenhouse gas in the construction industry?

A significant portion of global greenhouse gases are associated with the built environment, from resource extraction to the manufacturing of building materials, the operation of the buildings themselves, and the transportation systems that serve the way buildings are laid out and planned. Interestingly, tackling the embodied carbon of building materials offers great potential for near-term improvement, since those materials will account for about half of the climate impacts of projected new building construction between 2020 and 2050.

Realizing general contractors can reduce a project's embodied carbon more significantly than through operational improvements alone by choosing better materials from the get-go is a game-changer, especially when those lower-carbon options can cost about the same as the alternative and will be locked into a building over its lifetime.

Technology is proven to help make more sustainable choices – from early conceptual design through to build and operate. By using the cloud, design teams can visualize sustainability-related trade-offs with high accuracy. For example, the Embodied Carbon in Construction Calculator (EC3) is an open-source database to help designers and contractors choose lower-carbon materials. For the United States. to remain a leader in driving climate innovation, we need to promote the idea that digital and green transitions go hand-in-hand.

From a regulatory perspective, what policies (at a high level) do you see having the greatest impact on instigating positive change (regarding climate) in the construction industry?

The construction industry needs help to transform its processes and its workforce through digital tools to put climate first. Governments should provide incentives to drive digitalization, which enables energy modeling, carbon measurement, and carbon reductions in building operation, and to reduce waste throughout the design and construction process. And additional support is needed to train the workforce across disciplines in new sustainability-driven processes and integrated digital workflows to successfully achieve this vision.

How has the investment landscape for the built environment changed in the past decade? And what's your outlook for its future? How and where will we see public capital playing the most significant role?

We're advancing support for technology like digital twin, prefabrication, simulation and generative design, and other applications that aim to integrate manufacturing, engineering, construction, and architecture. We see a lot of promise for prefabrication, like what Factory_OS champions, where a company builds the components of a building or other structure at an offsite plant and assembles the pieces at the destination, like a Lego set. This approach to building leverages the efficiencies of manufacturing and promises to reduce the rework and waste that plagues the construction industry today. +

Interview

MARTHA CAMPBELL Principal | Carbon-Free Buildings, RMI
LUCAS TOFFOLI Manager | Carbon-Free Buildings, RMI

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What excites you most about the construction industry today? A material? A process? A philosophy?

Martha: I'm passionate about creating healthy, beautiful spaces and environments — and construction is a tool that allows you to do that. But the industry is at a breaking point; we're seeing a housing shortage and an environmental crisis. We cannot keep doing business as usual, and now is the opportunity to rethink how we create environments we actually want to exist in: beautiful, healthy, resilient, and sustainable environments.

Lucas: Building on Martha's points, Rocky Mountain Institute was founded upon on philosophy of integrative design — creating solutions that holistically address a set of challenges. There is a massive opportunity to do just that. And that's exciting! I can imagine a set of integrated solutions to address carbon, health, resilience, logistics, and business.

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How do you reconcile the competing challenges the built environment faces — that we need more housing quickly and that such housing, if we are to keep the worst of climate change at bay, needs to be holistically carbon neutral? That of course normally comes at a cost premium.

Martha: There are tremendous advantages to industrialized construction where waste reduction is concerned. 40% of current landfill waste comes from construction materials. Between now and 2030, emissions coming from building materials will roughly equal the emissions coming from operating those buildings. So a reduction in waste alone will have a massive impact. We can also go one step further and innovate with the materials themselves so that they have lower embodied carbon.

Lucas: The Advanced Building Construction Collaborative led by RMI and its partners is focused (although not exclusively) on industrialized construction — we look at it as a force multiplier for concepts in construction. It's the idea of bringing modern manufacturing methods and workflows to construction, which is an industry that, in many ways, hasn't changed for more than 100 years in the past. If you can intervene early with this approach, there's an opportunity to inject principles of low-carbon and efficient construction into a large volume of projects. Suddenly you have a tool that allows you to build quickly, responsibly, and efficiently.

There are opportunities for all sizes and types of players — incumbents to startups — with industrialized construction. There is so much work to be done that there will inevitably be a need for a combination of responsibilities and expertise.

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What emerging construction technology or process do you find the most fascinating? And which do you think has the greatest real-world potential?

Martha: I love the idea of 3D printing. There's something about its versatility, even for retrofitting, that is fascinating. One of the biggest challenges in retrofitting current buildings for greater efficiency is matching the geometry of the building itself, to retain its architecture. Imagine 3D printing a new high-performance exoskeleton for a building; you could integrate high-performance, low-embodied carbon insulation into a form factor that looks exactly the same as the existing facade. There are so many possibilities with the materials as well — new types of zero carbon cementitious materials, for example.

Lucas: I'm excited by the idea of multi-trade assemblies, where all trades work together in a choreographed dance (ideally in a controlled environment), eliminating scheduling bottlenecks and missed hand-offs. When you then deploy the subassemblies created in this way, you can deliver the assembly to the site when it's needed and have simple, easy-to-verify connections between assemblies. It potentially reduces waste and reduces areas of risk and uncertainty in both the schedule and building quality.

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From a regulatory perspective, what policies do you see having the greatest impact on instigating positive change in the construction industry?

Martha: Take a look at the federal tax credit for EVs — I think it's somewhere around $7,500 — then look at subsidies for energy efficiency for a home, if you're able to jump through the hoops and successfully apply for one, it's about $3,000. We are devaluing the decarbonization of buildings versus cars. We should create a tax credit that is proportionate to the value of a home and its environmental impact.

Lucas: Let's think of buildings, or parts of buildings, as a product. If you get a dryer, a furnace, or any other major appliance, it has a UL stamp or an equivalent, and you can install it anywhere in the country because of that certification. Now imagine the same concept for a larger piece of building — a module — you suddenly have an alternative compliance pathway, you have a certification that is broadly recognized, and you can meet code requirements without having to respond to a process that is written for stick-built buildings. +

There are opportunities for all sizes and types of players — incumbents to startups — with industrialized construction. There is so much work to be done, that there will inevitably be a need for a combination of responsibilities and expertise.

Interview

GREG SMITHIES Partner, Climate Technology Investment Team | Fifth Wall

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What excites you most about the construction industry today? A material? A process? A philosophy?

What really excites me is the size of the opportunity. Real estate and buildings are by far the world's largest asset class — there are $270T worth of buildings out there. We build somewhere between $5T and $8T worth of new buildings every year. If you're doing any kind of innovation inside this market, you can have a massive impact.

The best engineers in the world go and work at Facebook, even though their products are, you know, pointless. But the best and brightest go there, because if you build something, it has an impact on billions of people. If you're building stuff inside the built environment, you can literally move the needle on global supply chains — the largest segments of capital in the world. You can touch everyday lives.

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How do you reconcile the competing challenges the built environment faces — that we need more housing quickly and that such housing, if we are to keep the worst of climate change at bay, needs to be holistically carbon neutral? That of course normally comes at a cost premium.

It is a push and pull. Everything needs to happen as opposed to any one silver bullet — the market is too large for a single solution. You need the stuff that you can implement right now that perhaps doesn't solve 100% of the problem, but gets you down 20%, 30%, 40%. And then, at the same time, you need to be investing in the things that are going to come in a decade's time and solve the rest of the problem.

We must fix the materials industries at the center of construction — concrete, steel, and glass. These are massive emitters of CO_2, some of the top in the world. We can fix these industries by both finding fundamentally better alternatives and fundamentally better ways to make the materials. In the case of steel girders, for example, we could look at cross-laminated timber as a replacement. Or look at approaches like that of Boston Metal, which is creating zero-emissions steel with electricity.

We also need interim ways of solving these problems better — one of those interim approaches is using hydrogen. Just replace coal with hydrogen in steel production, for example. You can most likely do this faster than scaling Boston Metal globally. It will take probably 30-40 years to replace every mini steel mill with Boston Metal's technology, but replacing the coal feedstock with hydrogen can most likely happen twice as fast. In the long run, we probably need both solutions, and because the climate emergency is so dire, we should be pursuing both paths.

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From a regulatory perspective, what policies do you see having the greatest impact on instigating positive change in the construction industry?

There are two things that you can think of here — carrot regulations and stick regulations. Stick regulations, or fines, can be very good at getting people to care about something that they do not innately care about. For example, in Manhattan, we have local law 97 [most buildings over 25,000 square feet will be required to meet new energy efficiency and greenhouse gas emissions limits by 2024]. This law is probably going to cost landlords in Manhattan alone $10B in fines per year if they do not clean their buildings. That is a very effective way of making people care. But what it is not effective at is making new technologies economically viable. You can't use such regulation to take a technology that is 10X too expensive and get it down to making economic sense.

Carrot regulations, on the other hand, can actually move markets. These would be things such as energy efficiency retrofits like those mentioned in the U.S. infrastructure bill, which, even in its "skinny" form could have $150 billion in it for such programs. Why? Because they drive jobs. You can take a coal miner and train them how to replace windows in a building — a building in their current town. Some stats for context — if you take one million dollars and put it into the coal industry, you create on average four jobs; put the same money into clean energy and you create five jobs; and put the same money into energy efficiency retrofits and you create 15 jobs. So a carrot regulation in this example can create jobs and drive the cost of a technology down by pushing demand sky-high, hence bringing that technology down the economies-of-scale ramp.

> *We can still put 100X the amount of capital into the built environment than we are doing now. The market opportunity is tens of trillions of dollars, whereas the dollars chasing it are around $20-$30B for venture and growth. To compare, SaaS is an $800B market and you've probably got $200B worth of venture and growth capital in it.*

So, carrot regulations move markets, whereas stick regulations are good for awareness and getting people to care.

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Looking beyond the United States, who is "doing it right" when it comes to regulatory action incentivizing the adoption of clean energy technologies?

The German subsidization of the solar industry is probably the best example of this. Solar has come down 90% in price in the past decade, due in large part to Germany's subsidies. They put billions of dollars into solar 10 years ago, and that investment kickstarted an entire market and reduced its cost curve. It's a great example of how government work can spin up the economic flywheel.

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Which facet of the built environment faces the largest hurdle to decarbonize? Why is this? And who is proposing the most intriguing solutions?

There are two buckets here — new construction and building operations. You have to think of them as two discrete markets — one is an embodied carbon problem, and the other is an energy consumption problem. The embodied carbon problem, as we talked about earlier, can be solved by making the core building materials in better ways. If you do that, you've solved 90%-95% of the challenge.

When you look at the operating emissions challenge, it is essentially all about HVAC. It's not lighting anymore — it's HVAC and refrigeration. We're going to see the replacement of furnaces with heat pumps, the replacement of existing electric motors with more efficient motors, and the replacement of old refrigerants with more efficient green refrigerants.

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How has the investment landscape for innovation in the built environment changed in the past decade? And what's your outlook for its future?

The whole industry was ignored from essentially 2009 to 2017. We lost a decade because of the cleantech crash. But those companies didn't go away; it's just that VCs weren't backing them, so they had to find other types of capital — they figured out how to do things with debt and grants.

What has changed in the last three or four years is the rise of VC investment in the space once again, and with it, a more robust capital stack. The growth equity folks, the project finance people — they've just come back to it. It's fantastic. But we can still put 100X the amount of capital into it than we are doing now. The market opportunity is tens of trillions of dollars, whereas the dollars chasing it are around $20-$30B for venture and growth. To compare, SaaS is an $800B market and you've probably got $200B worth of venture and growth capital in it. That ratio makes no sense. +

↳ *Interview*

LEAH ELLIS

CEO & Co-Founder | Sublime Systems

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How do you articulate the true impact that cement production has on the climate?

Cement production is, quite literally, the elephant in the room in terms of carbon emissions. It is huge and it is grey. It's just colossal. Each ton of cement produced releases one ton of CO2 into the atmosphere — a cement factory could also be called a CO2 factory. And then when you realize just how omnipresent cement is, you start to realize the scale of the challenge.

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Sublime Systems is pioneering a new cement production process, one that is proven to work and one with tremendous potential. What do you see as the major hurdles facing widespread adoption of such a process? Policy? Technology? The incumbents? .

We are climbing two mountains. The first is achieving production at scale. To put that scale in perspective, the average cement plant makes one million tons of cement per year. And since it is such a low-cost commodity, any new player will have to produce their product at a massive enough scale to drive down cost in order to spur adoption.

The second mountain is the existing industry. The incumbents are tremendously powerful. They have billions of dollars of capital invested in their equipment, equipment that is impossible to abandon. The more cement incumbents push through their giant, expensive pollution kilns, the more money they make. They are not strategically aligned if you bypass their fossil-fuel-burning kilns.

But there is hope. Sufficiently disruptive technology that combines low-cost renewables with cutting-edge electrochemical technology can break through these challenges to achieve broad market penetration

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Who will be the first player in the construction ecosystem to make the leap to carbon-neutral or zero-carbon processes at an industrial level? A materials manufacturer? A multinational contractor? And how will such a shift affect the other players in the ecosystem?

It has to be the owners of the construction project. For example, organizations building major campuses like Google or Facebook or some other Fortune 500 company that will be using massive amounts of cement and wants to fulfill ESG corporate objectives to be aligned with something carbon neutral and disruptive.

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What nation and/or community is "doing it right" when it comes to decarbonizing construction? What forces will push others into doing the same?

Well, one example that I think of outside the construction industry is Tesla. They brought something radical into an entrenched sector. They were up against deep-rooted incumbents, trying to disrupt a commoditized market.

I see a lot of parallels there, except of course it will be much harder for Sublime because cement is much less sexy than a fast car. The people who care in cement are the engineers and architects, the leads. Those are the people who would slide a new product in wherever the standards permit them.

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What has most surprised you as an entrepreneur in the construction materials sector?

Many incumbents cannot see another way of doing it. Technically, I don't see why it can't happen — we've proved our platform works at the kg/hr scale, and similar electrolytic processes have been used for decades in other industries. So all this nay-saying is sort of like water off a duck's back. We as a team also gravitate toward the hard things. We're not doing this because it's easy. At Sublime, we're aware that the challenge before us is massive. But we also know it is possible. +

Interview
MATEO ZIMMERMAN Investment Manager | CEMEX Ventures
GONZALO GALINDO CEO | CEMEX Ventures

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What excites you most about the construction industry today? A material? A process? A philosophy?
Mateo: Solving the root problems facing the construction industry excites me. Two such problems are fragmentation and lack of collaboration. When an industry as diverse as ours is fragmented, there is a misalignment of interests — who benefits from what? This misalignment creates shadows — limited insight into what fellow members of the industry are doing. If we truly want to make change, we must improve the way the industry communicates.
Gonzalo: I don't know if industrialized construction is the ultimate solution, but certainly the concepts of connecting, communicating, and everybody working together in a system are valuable for any stakeholder in the construction industry. Every time we talk about innovation in the construction industry, it's all about the big project — the bridge, the high rise, and so on. But the fact is that the process of construction around the world is mostly a one-person show — building an extension of a room in the outskirts of Mexico City, for example. And they have the same problems — the lack of connectivity, the lack of information. To me, it's about the process and the way you approach every single project, no matter the size.
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How do you reconcile the competing challenges the built environment faces — that we need more housing quickly and that such housing, if we are to keep the worst of climate change at bay, needs to be holistically carbon neutral? That of course normally comes at a cost premium.
Gonzalo: That is the $64M question! I think, moving forward, that is one of the hardest things to do. The sustainability charge will cost a lot of money. But we have to do it. Otherwise, we might end up with a world full of houses with nobody living in them because everybody will have succumbed to greenhouse gas emissions.

Addressing such challenges will require consolidating the needs and capabilities of everybody involved — all the way from governments to contractors to people like us who are building materials producers — trying to come up with a solution that works best for everybody. It will require significant R&D to ensure solutions are tested and proven in advance of widespread deployment, as well as government collaboration.

For example: If we want to get better at recirculating materials, we need more powerful waste management and landfill laws that push people to think about recycling as an economically sensible option. Some countries like the UK and Germany, for example, already have such laws. Whereas here in the United States, many states and municipalities don't care. There is no economic incentive to change.
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These are multi-factor problems. Achieving carbon neutrality is not as simple as just innovating in one area. Taking that complexity into consideration, who or what do you think will be that first mover? Will some miracle material be invented that reaches cost parity with current materials and spur larger change? Or do we require some regulatory body to take the first step?
Gonzalo: Good question — I think it will be a combination of players, from those in building materials to oil companies and beyond. We are seeing financial analysts and tracking share prices of large equity funds like Blackrock that are saying, "we will not invest in companies that are not taking climate change seriously." That has triggered significant concern.

In some instances industries are more naturally positioned by virtue of their capability (those who handle gases may find it easier to manage CO_2, for example), whereas others will need to implement solutions from scratch.
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What players within the construction industry face the most significant hurdles in their journeys toward decarbonization?
Gonzalo: It depends; how decarbonized do you want to be? Many people are saying they will reach net-zero emissions by 2050, but what does net-zero really mean? I predict that we will be at "net" zero but not zero-emissions.

Building materials producers, especially those that depend on mining resources like glass, steel, and cement, will lead significant efforts and put very strong processes in place. Logistics on the other hand, may not sound as crazy, depending on which type of electricity they are using. But there will be challenges electrifying the transportation chain in places with infrastructure similar to countries like Bolivia, Mexico, or even Spain.

Contractors, in my view, have the simplest path, because they can always claim that they are not the ones generating the CO_2 — it is the responsibility of those producing and transporting the materials.
Mateo: You cannot forget renovations and retrofits to the world's existing buildings. There is a lot of work to be done to increase the efficiency of those buildings — work in roofing, insulation, heating, and so on. Look at how many buildings are built in a year, then look at the number of existing buildings in the world. All of those have operational emissions that continue for decades. That's the elephant in the room, right?
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What foundational, enabling technologies that may be evolving in adjacent industries will have the greatest effect on the construction industry? AI, ML, another digital technology?
Gonzalo: I have a very personal view on that. I think that the digital era is beginning to finish [in the construction industry] — the real technological breakthrough will come on the environmental side. If we want to achieve the amount of housing we need at a decent price in a sustainable way, we will need the best hardware to do so. There are also most likely technologies already familiar to us, but not currently being applied to the construction industry. For example, we can still do a lot with 3D printing. The approach is far from mature, and we do not fully understand how best to use it in the built environment.
Mateo: We learned a long time ago that it's not about the technology but about the problem you're solving and the product / market fit. We're [at Cemex] technology agnostic; we're more focused on pain points.
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Is there a technology that you're rooting for that is not yet commercially viable?
Gonzalo: It's not that the solutions are not there; the question is if we will be able to apply those solutions everywhere. For example, CO_2 management; once you capture CO_2, you have to put it somewhere. What happens if you are not near a storage area? You must start to create an ecosystem around your physical plants to help you make use of that captured CO_2 — hopefully there is a soft drink company next to you. [Laughs]

Even if we figure out solutions that will help create an environment of transparency, we may not be able to apply them everywhere. I come back to the example that two-thirds of construction is performed by a self-builder. All self-builders want is a roof — they do not have to ability to mitigate emissions the way large companies can
Mateo: How do you bring innovation into construction when all of the norms say to build with concrete and steel? And if you're doing something new, then you need to add safety factors, which essentially make those new ways less competitive. I recently spoke to a company trying to do off-site construction with new materials — so new process and new materials at once. That is really, really difficult to do because the construction industry is so risk averse.

That's why we look for technologies and approaches from those who really understand the construction industry — those who understand from the inside out how to make it better. +

When an industry as diverse as ours is fragmented, there is a misalignment of interests — who benefits from what? This misalignment creates shadows — limited insight into what fellow members of the industry are doing. If we truly want to make change, we must improve the way the industry communicates.

Interview

ISRAEL RUIZ CEO & Co-Founder | WoHo
DÉBORA MESA MOLINA President & Co-Founder | WoHo

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What excites you most about the construction industry today? A material? A process? A philosophy?

Israel: Two things: one is the centrality that it plays in our lives. The pandemic has made us all now super aware of the physicality in which we live. And the other is the opportunity to change the way things have been done. The construction industry is probably the last one standing in terms of improvement, especially when it comes to integrating technology. That challenge is exciting.

Débora: We are in a moment of forced transformation. The construction industry has evolved without much consideration to issues that, today, cannot be ignored. As an architect, I am particularly excited about the new tools and materials available to us. They give us the opportunity to preserve quality and the functional beauty of design, while also helping solve greater issues like climate change — innovation is needed, invention is needed, and architects can have a strong voice in engagements with the larger construction industry.

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How do you reconcile the competing challenges the built environment faces — that we need more housing quickly and that such housing, if we are to keep the worst of climate change at bay, needs to be holistically carbon neutral? That of course normally comes at a cost premium.

Israel: The reconciliation of a complex problem can only come from every stakeholder arriving at the table and playing some role. The challenge you highlighted is exactly right. At the heart of it, we're trying to solve a housing problem, as well as a climate problem. There are different paths we can take to get there, as well as different human values and ideals.

I happen to believe that if we're going to go and solve for a single-family home, we're never going to get there. And even if we could get there by doing so, the impact of the additional one-at-a-time type of homes will be much more magnified. By uniting technology, process, and what I call a "coalition of the willing," we can start making a significant impact. And this impact can be measured and trusted, instead of simply checking a box. This will not be a short journey. But it will be a determined one.

Débora: It will be a learning process. It is not possible to flip the switch completely with the first project, but there are many small steps that, together, will have a massive impact. At WoHo, for example, we know that we can innovate with some of the most controversial and massively used materials, such as concrete, there are already improved formulas, but the problem is the codes have not evolved enough to understand them — the industry has not tested them enough in large-scale projects. The solutions are out there, but regulations need to catch up to use them fully. We can, however, start testing some materials in certain non-structural parts of buildings.

We can also work on the fabrication and assembly of buildings. Making these processes more efficient will save time, reduce waste, and cut emissions. We are always moving forward, even though the construction industry at large is risk-averse. I do believe, however, that change in the industry will accelerate to address the simultaneous crises in climate, housing, and labor.

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Who is in this "coalition of the willing"?

Israel: It takes a value chain approach — from the raw materials, like the cement manufacturers or the manufacturers of lumber and woods, all the way up to creating the elements, the systems that build a building. And then it comes to the communion of the architects, engineers, and contractors to take those elements, those materials, those systems, and put them together in a very specific way. It also requires the regulators for all those stakeholders I just mentioned to be aware of how to do things more efficiently, more affordably, and with much more of a climate orientation.

↳
Who will be the first player in the construction ecosystem to make the leap to carbon-neutral or zero-carbon processes at an industrial level? And how will such a shift affect the other players in the ecosystem?

Israel: I think we'll need to take a little bit of a cue from international relations and multilateralism. To establish a coalition or a multilateral collaboration, you need to engender trust. If you don't have the trust in that coalition, in those partners, you're really never going to get anywhere.

I am of the view that a comprehensive vertical approach like Katerra pursued is too much to take on. And then the other extreme is to have a government agency or regulator take that role. Here again, my sense is that such an approach will not work due to a lack of trust. That leaves us with something that's more at the center, a collaboration led by a non-profit of some sort. But that approach also has potential pitfalls concerning the lack of traction and speed.

I believe we must bring together innovative technology and a team with chops, like WoHo has, with strong economic and climate propositions, and demonstrate not that we can disrupt an industry, but that we can prove a path to success. Proving the path is essential because every single one that has been tried before today has failed.

Débora: Governments — they are the ones that can move markets through policies, tax incentives, subsidies, and grants. Once they start making moves, the other stakeholders will get on board.

↳
From a regulatory perspective, what policies do you see having the greatest impact on instigating positive change in the construction industry?

Israel: Unifying building codes. In the United States you have 50 jurisdictions with 50 different codes. If you build in New York versus New Hampshire versus Massachusetts — in a span of 300 miles you have at least three different building codes. If you are a manufacturer and are trying to optimize your building process, you will by definition overengineer. You will choose to design to the most stringent code.

Débora: Codes. But these codes are also tied to culture. We have to look at codes and culture simultaneously — how can codes help us create buildings that engage the user and make building operations smarter?

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Which facet of the built environment faces the largest hurdle to decarbonize? Why is this? And who is proposing the most intriguing solutions?

Israel: I have a very strong view on that — the most significant impediment to progress is a lack of honest accountability. There is no standard by which you can actually measure the climate impact of construction projects and building materials. That's a real problem. Without such standards, we are susceptible to what is marketed to us.

For example, I recently read a piece that proposed CLT [cross-laminated timber] construction is "better" than cement. A statement like that discounts the progress we are making in net-zero cement. And it fails to account for the other materials needed to make CLT structurally sound, the transportation of those materials, and the use of those materials. So are we talking about the appearance of sustainability or the facts of such sustainability?

Débora: Many processes have been overlooked because of a lack of holistic understanding, coordination, and integration. The solutions must involve everyone, including those living in the homes. We must think about the built environment across the entire lifespan of a building, construction, and operation. How can we make the system as a whole more efficient?

It is no longer a question of having the tools — it is a question of perspective and agreement. The industry must become more unified, just as a building is a set of systems working harmoniously together. We must isolate any potential liabilities and innovate together.

↳
What is the most unexpected source of GHG in the construction industry?

Israel: I think there are two. The first is waste and inefficiency due to a lack of precision, unified codes, and unified processes. The second is transportation, especially with building materials.

If you look around, chances are you'll see a stone façade or marble flooring from Italy or the interior design reliant on furniture from a Scandinavian country. We don't "count" the transportation emissions of those things. But we should.

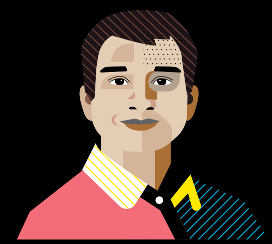
Débora: Fragmentation and redundancies. So many tasks are unnecessarily fragmented and redundant. The impact of this is difficult to measure. For example, it is accepted that new construction will have around 20% waste. Design and fabrication are usually not integrated, and the same happens with logistics; very few of the trips to move goods on-site or offsite are coordinated, producing unnecessary transportation emissions and costs.

↳
How has the investment landscape for innovation in the built environment changed in the past decade? And what's your outlook for its future? How and where will we see public capital playing the most significant role?

Israel: There is very little money going into innovation in the built environment. Most of the money goes to the transactional layers — buying, selling, and funding real estate. If there is any innovation money that goes into the building technology itself, it is mostly self-funded out of contractors or early-stage companies. But once we can start putting forward pathways that demonstrably create efficiencies, private money will be like a flip of a switch — it will go from zero to one, quickly. +

By uniting technology, process, and what I call a "coalition of the willing," we can start making a significant impact. And this impact can be measured and trusted, instead of simply checking a box. This will not be a short journey. But it will be a determined one.

PATHWAYS TOWARD A CO_2-FREE ENERGY ECOSYSTEM



BY *Amrit Jalan*

INTERVIEWS BY *Nathaniel Brewster* | ILLUSTRATIONS BY *Julie Carles*

From those primal days huddled around a fire for warmth or harnessing the power of the sun to preserve hides and food, humans and human evolution have been inextricably tied to the energy ecosystem. Today, we demand more energy, in more places, than at any other time in our history. Yet the challenge of satisfying this demand runs headlong into the existential crisis of climate change — how are we to satisfy the demands of future generations without resigning ourselves to an uninhabitable planet?

The path to a carbon-free energy ecosystem will not be easy — success will require internalizing lessons from the past and present. Understanding historical energy flows will not just help us appreciate the inherent complexity of the modern energy economy but also guide us in picking the right metrics, testing the right hypotheses, and enabling the right discussions with multiple stakeholders in this global ecosystem.

THE ENERGY VALUE CHAIN

In its simplest avatar, the energy ecosystem is best viewed as a sequence of linear events.

The 'Source, Transport, Use' paradigm provides a useful lens to examine how the energy value chain has evolved over the centuries to its present form and what changes will be necessary in a low-carbon era.

SOURCE

The supply side of the energy equation captures all the effort required to harness energy from sources as simple as wood to complex offshore rigs for oil or uranium for nuclear fuel.

Our primary energy supply comes from a surprisingly finite number of sources:

- Chemical bonds: oil, gas, coal, wood
- Nuclear material: fission and fusion
- Light: solar energy
- Kinetic energy: wind
- Potential/gravity: hydro
- Heat: geothermal

TRANSPORT

Once harnessed, energy needs to be moved to the point of end use. Despite centuries of innovation, we essentially move all our energy either in the form of chemical bonds (e.g., gasoline and diesel) or electrons (millions of miles of wiring across the planet).

While moving energy may sound simple, it requires a significant amount of capital and infrastructure (e.g., electricity grids, vast networks of oil and gas pipelines, and gas stations).

Note that not all forms of energy are transportable. Solid/liquid forms are easier to transport, while heat energy travels poorly as it is easily lost to its surroundings.

USE

The demand side of the energy equation captures all human activity that involves the use of energy in some shape or form. It includes mobility, heating/lighting, and increasingly the use of energy for data and computation, across both personal and commercial end uses.

The demand side can vary significantly between countries, depending on population, economic output, and quality of life.

Note that significant amounts of energy are wasted due to anthropogenic inefficiencies and to the core principles of thermodynamics.

CHEMICAL BONDS (C-H,C-C)
· oil
· gas
· coal
· biomass

NUCLEAR fission/fusion
LIGHT(PHOTONS) sun
KINETIC ENERGY wind
POTENTIAL/GRAVITY hydro
HEAT geothermal

→ **CONVERSION** →

CHEMICAL BONDS
· gasoline
· diesel
· natural gas
· hydrogen
· ammonia

ELECTRONS

→ **DISTRIBUTION** →

KINETIC ENERGY (MOBILITY)
· personal
· commercial

HEATING/LIGHTING
· residential
· commercial
· industrial

ELECTRICITY
·computing

WASTE

THE STATUS QUO

Until the 19th century, the energy ecosystem was powered primarily by wood and coal. Advances in our ability to drill into the Earth's surface and extract oil and gas led to the momentous rise of these resources in our supply mix. This rise was furthered by demand-side inventions (e.g., automobile, rise of commercial shipping, and aviation) and supply-side innovation (e.g., refining, off-shore drilling) leading to an increasingly nuanced energy ecosystem.

The supply and demand sides of the energy ecosystem are like two different representations of the same puzzle. The key difference is that the supply side involves a small number of large pieces (carbon-based chemical bonds, nuclear, biomass) while the demand side involves an astronomical number of small pieces (anything that requires energy).

SOURCE

80% of US primary energy supply comes from carbon-based sources like oil, gas, and coal. Of the 100 quadrillion BTUs (known as quads) of energy that we use every year, roughly **80 quads** are supplied in the form of C-H, C-C chemical bonds while the remaining 20% gets distributed between renewable sources like nuclear, solar, hydro and wind.

The reason for the popularity of carbon-based sources is simple: when burned, these fuels release vast amounts of energy as dictated by natural laws of physics. These fuels are also inexpensive and relatively easy to obtain, refine, and combust.

TRANSPORT

Of the 100 quads of energy supply, **37 quads** are transported in the form of electricity to various demand centers.

The other **63 quads** are moved in the form of chemical bonds (think gasoline and diesel) for the simple and practical reason that chemical bonds are highly dense, meaning more energy can be transported more efficiently.

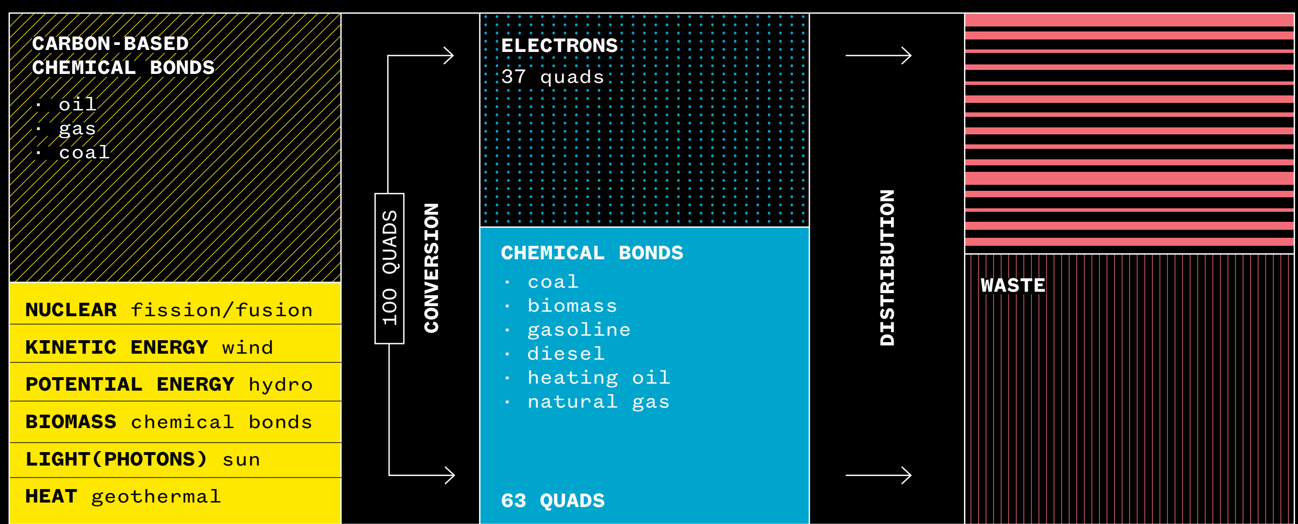
USE

The demand side of energy use in the 21st century is fragmented and spans a vast network of use cases, including **personal, commercial, and industrial uses.**

The demand side of energy involves over **one billion machines:** everything from cars, trucks, and planes to cell phones, dishwashers, and water heaters.*

Just over 50% of the energy supplied in our economies is wasted. While many cite this as a major problem, it should be noted that energy efficiency is a way to reduce the carbon intensity of a carbon-based energy system. It is critical to remember that carbon emissions are primarily a supply-driven problem, and it is equally if not more important to decarbonize our supply sources.

**As estimated by Saul Griffith in his handbook "Rewiring America."*



THE FUTURE

What could a CO2-free energy ecosystem look like?

The fundamental source of carbon emissions is the carbon-heavy supply side of the current energy ecosystem. As a result, any CO2-free energy system must either rely on carbon-free primary sources or mitigate CO2 emissions from fossil-based primary sources. Almost immediately, the size of the problem becomes clear. We need to find a way to replace the 80 quads of CO2-intense primary energy supply — approximately 80% of total U.S. energy consumption in 2019 — that are currently coming from carbon-based sources with a combination of clean sources and mitigation measures.

— Pathway 1 —

ELECTRIFY EVERYTHING

We know how to produce green electrons from solar, wind, and other renewable technologies. Such sources have become increasingly cost-effective and reliable to operate. Other zero-carbon dispatchable sources like fusion energy and supercritical geothermal are quickly approaching commercial viability.

But the effort required for and implications of undertaking such a transition cannot be overstated. Only with significant policy changes and enhanced public/private partnerships will we be able to adapt our infrastructure (think: transmission lines, electric vehicle charging stations, land allotments for solar and wind farms) at a scale and speed necessary to make effective change.

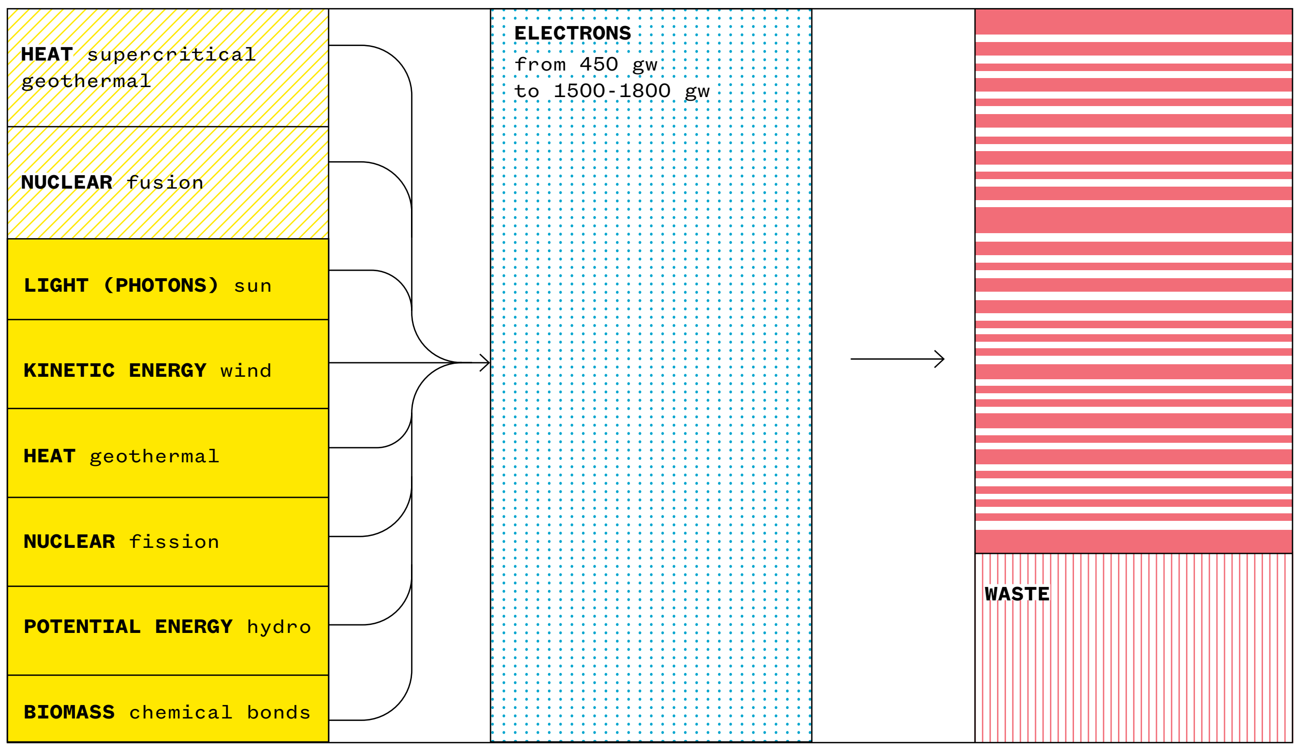
SOURCE
An energy system with electricity as the sole carrier of energy will require quadrupling our existing electricity supply from **450 GW to 1800 GW!**

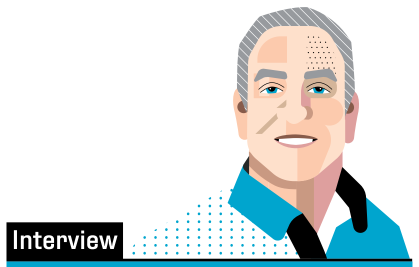
Supply sources like **solar, wind, nuclear, geothermal,** will need to be **developed and deployed on massive scales.**

TRANSPORT
A distribution infrastructure that can handle increased loads and inherent intermittency of several supply sources.

The current grid has largely operated under the convenience of certainty guaranteed by fossil fuels. It will need to adapt to a future where supply sources are **smaller, distributed, and more interactive.**

USE
Every machine requiring energy will need to be redesigned to work with electrons. While this is possible for several end uses, electricity may not be the energy source of choice for a number of applications (e.g., shipping, aviation) for several reasons (technology, operations, costs, complexity).





Interview

ADAM WALLEN

CEO & Co-Founder, VEIR

VEIR is reinventing the architecture of electricity transmission to enable a fully decarbonized grid.

Electricity transmission is invisible to the vast majority of us…until it stops working. Can you help us set the scene? How did we get to now? What did those innovations look like?

The last innovation goes back to Edison. I jest, but the innovations in our sector are related to demand — the greater the load, the more power required, and accommodating that increase in power means making more robust traditional metal conductors and deploying them at ever increasing voltages. Fifty years ago, the state-of-the-art was a 138kV line and now high-voltage transmission is 345kV and greater. This means we need larger rights-of-way and taller towers; you need larger margins around these lines. We're even seeing lines in the >1,000 kV range in parts of China. Innovation in this area is mostly around "high temperature, low sag" conductors.

Smart grid applications have also arisen in the past decade or so. These platforms help us use our electricity more efficiently by managing surges in load to flow electrons better through the existing wire infrastructure.

What needs to change with regarding to the interplay of regulation and innovation to help us electrify everything?

The government can help stimulate innovation by working with utilities, regulatory bodies, and legislators. Utilities, from a regulatory perspective, are measured on the reliability and durability of their systems. Electricity is a critical infrastructure, and consumers expect extremely low downtime; keeping the lights on is priority #1, and utilities can be penalized in regulatory proceedings when reliability suffers. They are not incentivized to adopt new technologies. And if there is an innovation that they want to put into their rate base, they must prove to regulators that such an innovation is not a reliability concern. Put simply: no innovation in the power space will be integrated into the grid until the utility feels comfortable with it.

Such risk can be mitigated by the creation of new programs by the Federal Energy Regulatory Commission (FERC) and state regulators that incentivize the evaluation and demonstration of new technologies, particularly in places where they provide added redundancy without disturbing the active grid. New incentives may be needed because in these locations or testbeds, the technologies may not immediately provide benefits that fully justify their installation. The Department of Energy (DOE) and similar government agencies can also implement loan guarantee programs for new technologies.

Let's say these three groups — utilities, regulatory bodies, and legislators — cooperate to drive innovation? What does such an ecosystem look like?

All three recognize the fact that if we want to electrify everything, things must change. There are outstanding questions regarding streamlining permitting processes — will it be at FERC or outside of FERC? But all these groups understand that innovation must come. We cite the Princeton University study finding that we'll need to double the capacity of the grid if we are to simply meet business-as-usual electrification goals; if we look at a high-electrification case in 2050, we'll need to triple the capacity of the grid. All the stakeholders recognize that it is going to take a coordinated effort to find the right capital, to do the demonstrations, and to prove the robustness of any new technology plugged into the grid.

Why haven't we seen HTS transmission lines before? And what's changed regarding to their commercialization today?

In the late 1990s and early 2000s the DOE funded a huge amount of research into HTS in general at the national lab level. But the DOE's program ended about a decade ago, which slowed innovation in the sector.

There are over a dozen HTS transmission projects globally. All those deployments are underground and short-distance solutions for urban use. Think about a densely populated urban setting like Manhattan or Chicago, for example; it would be hard to bring in a new 345kV line, you must use existing civil works. You must pull out the old underground conductors and put HTS in; then you can achieve a 5X increase in the amount of power you can get into an urban core.

Past HTS transmission projects (and others overseas) are closed-loop systems and must be cooled with bespoke cryogenic plants. And due to the thermodynamics of underground systems, such plants cannot be more than ten miles apart. VEIR, on the other hand, is an above-ground open-loop system. Our system requires us to refresh the liquid nitrogen refrigerant, but at distances greater than 40 miles apart.

There seems to be considerable momentum, both political and technological, toward a CO2-free energy ecosystem. What could get in the way of such a future?

Everyone seems to agree that transmission is needed. The transmission lines on the grid in the United States are, on average, 40-50 years old — well beyond life expectancy. Transmission is needed in every state, whether it is blue or red. But no legislator wants to go into his or her district and say, "we're going to put a 200-foot transmission tower next to your house" to accommodate electricity demand.

Our messaging is consistent: if we want to meet decarbonization goals, we need more transmission. Wouldn't you want to do that with technology that looks like distribution [smaller, street side lines? Transmission is a common denominator that unites various infrastructure policies and creates new jobs, while, with our technology, eliminating legislative headaches and "not in my backyard" complaints. +

— Pathway 2 —

GREEN ELECTRONS + SYNTHETIC CHEMICAL BONDS

Electrify the energy ecosystem, to the greatest extent possible (depending on location-specific resource availability, costs, policy incentives, etc.) while developing alternate liquid and solid fuels that are carbon-free.

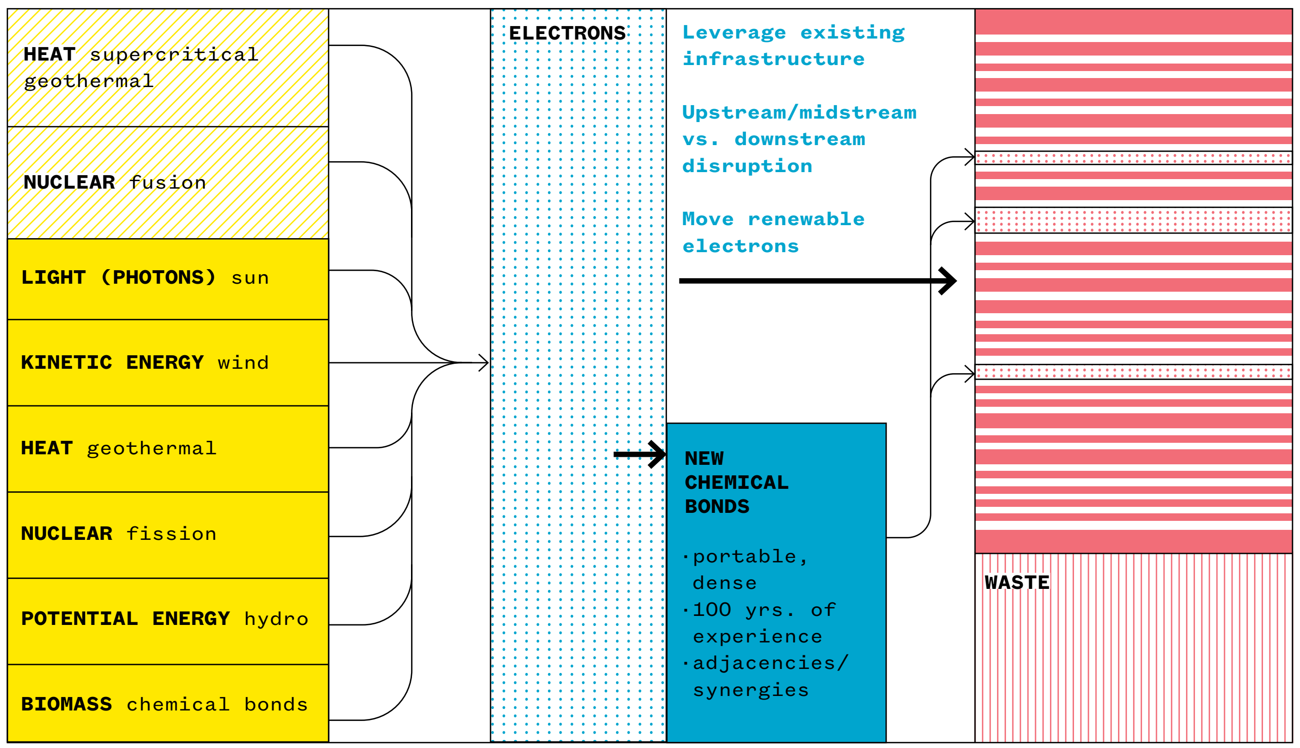
1 > Leverage adjacencies and synergies with existing infrastructure (e.g., fuel distribution)
2 > Move disruption upstream in the value chain to create invisible change on the demand side
3 > Move renewable electrons cheaply and efficiently to areas where they are in short supply

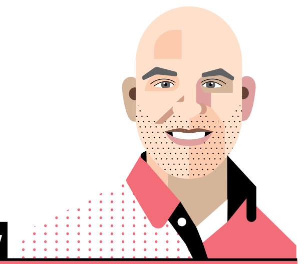
There are sectors like heavy-duty marine transport, commercial air travel, and heavy-duty industrial vehicles that because of their capital cost and established infrastructure, will be especially slow to transition to electric propulsion platforms. Alternative liquid fuels and hydrogen can provide emissions-free options that are significantly easier to integrate into existing frameworks.

SOURCE
Scaled-up carbon-free sources of electricity (see Pathway 1).

TRANSPORT
Technologies that can convert electricity and heat into portable chemical bonds like synthetic carbon fuels, ammonia, hydrogen etc. Retrofitted distribution channels to work with new fuels.

USE
Phased electrification of demand side depending on cost and availability of substitutes.





Interview

ROGER HARRIS

VP Technology Commercialization
Cemvita Factory

Cemvita Factory is applying synthetic biology to decarbonize heavy industries and reverse climate change.

Can you explain the challenges of decarbonizing the chemical industry and how Cemvita's platform can help us remove one gigaton of CO2 by 2050?
In order to successfully decarbonize industry, we must have a true understanding of the source of CO2. Heavy industry is responsible for almost a third of the CO2 emissions worldwide each year; that's approximately 10 gigatons — a huge amount!

We must also understand that even if we had a giant green button that could stop all CO2 emissions today, the CO2 concentrations already in the atmosphere will trigger severe weather consequences similar to what we are already seeing.

We're looking to become a plug-and-play solution, working hand-in-hand with our clients to use CO2 as a negative cost feedstock through bio-engineering. We want to make the building blocks that people are already using in the chemical industry — people will be able to stick with the plastics that they are familiar with, but those plastics will no longer be made from fossil fuels. We can make products that are very much in our clients' value chain.

Can you shed some light on that process? And what other chemicals are you making?
We've passed a watershed moment in genetic engineering. We're seeing the ability to generate genetic information, understand that genetic information, use that genetic information, and manipulate that genetic information. All four of those abilities are on an increasing exponential curve like we saw in the 1980s and 1990s with computing processing speed and power. They also are following the computing paradigm of an exponential decrease in cost. So we now have the ability to understand and generate genetic materials at incredible speeds for incredibly little money.

Our bioethylene project is up and running, but we see ourselves as a platform company, having a range of molecules that are created through our biological processes in collaboration with industrial partners. It's about coming up with the molecules with the greatest potential value for our clients — and one that is easy to fit into their existing processes.

The chemical industry seems, from the outside, to be full of powerful incumbents with established processes and significant capital invested in hardware. What's compelling them to change?
I am an optimist — I would like to think that everyone sees the global issue at hand and realizes that we must move toward a sustainable end goal, which starts with transitioning to CO2-neutral and CO2-negative technologies.

There's a lot of learning that needs to be done on the part of the end user. Many people don't know that throwing out a single-use plastic cup or bottle is actually contributing to CO2 emissions. With that education will come pressure for manufacturers to change.

We'll also see action from a regulatory standpoint. Punitive CO2 taxes will play a wider role than we are witnessing today. I've been in discussions with a few large petrochemical organizations, and many have indicated that if there is a carbon penalty and a carbon solution, that have similar costs, their investors and their customers would much rather see them doing the right thing.

How do you see the relationship evolving between you and the large, established industry players? What does that relationship look like in 15 or 20 years?
First and foremost, we want to collaborate with heavy industry and the existing incumbents. There are big players with big money that are looking to move away from fossil fuels — we've seen a $1.3T disinvestment in the space over the last few years. We provide them with a transition option, so they can create roadmaps for CO2-negative products over 5, 10, 25, or 50 years.

We also hope to empower small operators to adopt our technology in a distributed fashion, to find the regulatory framework that works best for it, and to implement it there safely, and cost-effectively.

What are the greatest challenges with the large-scale commercialization of chemicals and fuels produced via synthetic biology?
In our case, there is no way to escape the fact that CO2 is a fully oxidized, zero-energy molecule. It is difficult to work with such an inert feedstock. The second challenge is trying to bring new technology into an industry that is inherently risk-averse. The fossil fuel industry has been boiling oil for over 100 years, and there are $6T worth of assets that still have significant life to them. We must give our customers the sense that all risk has been mitigated and that we're not creating a dead asset. Finally, the volumes we're talking about are immense. Any undertaking to replace even a small piece of the pie is going to require a big capital investment. And that will take a lot of courage from the first mover.

Is it possible to unite a sector with so many players with such diverse interests?
The CO2 issue is so difficult because it is at once a global and regional problem. There is a massive imbalance between those responsible for and those experiencing the most negative effects of climate change.

We all must commit to the science and accept that there is a situation in need of remediation. And that remediation is more than just slowing down what we're doing; it involves reversing what we've done. Thankfully, we have the tools to truly optimize CO2 capture in a structured and programmable manner. +

— Pathway 3 —

GREEN ELECTRONS + GREEN FUELS + GREEN HEAT

Supplement electrification and synthetic fuels with direct geothermal heating to minimize conversion and distribution inefficiencies. Utilize local heat production while leveraging existing heating and cooling infrastructure.

Small-scale geothermal climate control platforms have already been successfully commercialized worldwide. The United States. currently offers a federal tax credit of 26% through 2022 on geothermal systems for homeowners. Companies like Dandelion and ClimateMaster are streamlining system purchase and installation. Further market adoption is not limited by technology readiness.

Other, more technically ambitious geothermal approaches, like those being commercialized by Quaise Energy (see sidebar), promise to provide zero-carbon electricity at terawatt scale.

SOURCE
Technologies to mine geothermal heat efficiently and at scale, anywhere on the planet.

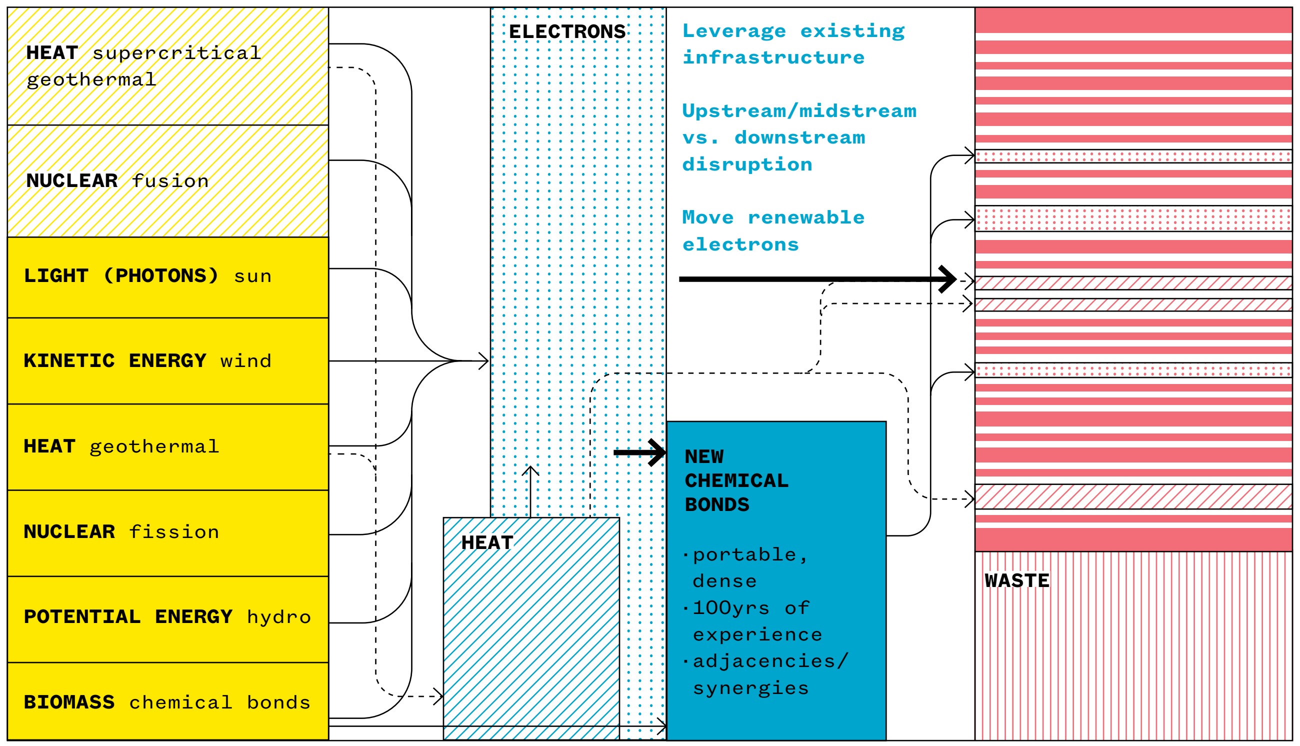
Electrification and synthetic chemical bonds noted in Pathways 1 & 2.

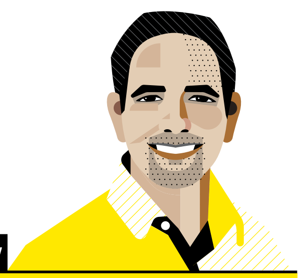
TRANSPORT
Infrastructure to deliver geothermal heat to residential, commercial, and industrial end-uses.

Transport solutions for electrons and synthetic chemical bonds noted in Pathways 1 & 2.

USE
Retrofit solutions for existing heating and cooling equipment to work with geothermal heat instead of fossil-fired heat.

Phased electrification noted in Pathways 1 & 2.





Interview

CARLOS ARAQUE

CEO & Co-Founder, Quaise Energy

Quaise is developing millimeter wave drilling systems to unlock supercritical geothermal energy everywhere in the world.

Can you explain the importance of supercritical geothermal energy in the clean energy transition?

Supercritical geothermal energy is as power dense as fossil fuels and as clean as renewables. It is the most abundant clean energy source on the planet and can play a vital role in transitioning our global energy system away from fossil fuels. Quaise intends to unlock this energy source through its novel drilling technology, which can go deeper and hotter than ever before possible. By going deeper and hotter, geothermal becomes truly global and power dense, which means it takes less time, less land, less material, and less labor to build clean capacity than incumbent technologies. All of those things are hugely important when you are talking about the terawatt scale that the clean energy transition requires.

What does energy utopia look like? And what's stopping us from reaching it?

Imagine going into a gas power plant and saying, "we're going to make a small geothermal field around you, and we're going to make that geothermal field produce steam — exactly the same steam that your turbines currently consume — so stop getting your steam from the furnace by burning fossil fuels and start getting you steam from the ground."

We can convert power plants at the rate of dozens per year, so the energy transition will accelerate greatly. And we would be doing this with a fraction of the effort of the shale revolution in the oil and gas industries in the last decade. A fraction of that effort can convert the entire fleet of fossil fuel power plants in the United States within 10 years. Now, that's scalability at the rate that the energy transition requires.

Can you speak more to the "effort" of the shale revolution? Are you referring to time and money? Human capital?

By effort, I mean what it took for an entire industry to mobilize materials and labor to meet a goal. The United States became the world's top producer of oil and gas because the oil industry was able to produce oil in new ways using the existing workforce, existing tools, and existing assets. They closed the technology gap of being able to extract oil and gas from impermeable geological formations — and when they closed that gap, everything else was already in place to support a massive boom. Prior to this, the idea of creating permeability in impermeable rock to pull fluids from that rock was considered economically and technically impossible.

To put the effort into perspective, the U.S. alone was drilling 30,000-50,000 wells per year to extract oil and gas. At Quaise, we're talking about drilling 1 thousands per year to meet the same demand and taking advantage of existing oil and gas infrastructure to deploy geothermal extraordinarily fast.

What needs to change regarding the interplay of regulation and innovation to get us there?

We need to treat geothermal like we treat oil and gas. Period. It is vital that geothermal becomes as simple, seamless, and quick to do as oil and gas, which is the result of 100 years of regulatory improvements. Put it in the same bucket. Put it in the same category, and we're there.

What does a partnership between an energy upstart like Quaise and an incumbent look like?

Power companies are finding themselves with fewer and fewer options with respect to their existing fossil-fired thermal generation. They've got to do something about it. We're saying, "Hey, you don't have to write off those assets — those thermal power plants — we'll repower them for you and you can continue using them." The alternative for them is to write off those assets.

What gives you hope of a greener, more verdant future?

The fact that there are viable solutions on the table today. If fusion weren't in development, or deep geothermal weren't possible, then I'd be concerned. I would be concerned that we'd be transitioning to an energy landscape anchored by wind, solar, and batteries. Such a future would have deep ecological consequences — as profound as the consequences we are experiencing today — because traditional renewables do not have the power density — the land, labor, materials, and time per unit of energy — that are needed for this global energy transition.

I believe that we cannot have a more prosperous world if we make backward progress with regard to power density. If you accept that statement, then you must find solutions with a power density as good as or better than fossil fuels.

Many of those communicating these big-picture visions struggle with capturing the scale of the challenge. How do you truly capture that scale?

We need to understand what a terawatt is a million megawatts. It's staggering. The entirety of the United States uses about one terawatt, and it's taken us 100 years to get there. And we're talking about an energy transition at a far greater scale.

To put a terawatt into further context, the oil and gas industry, just to maintain the status quo of 100 million barrels per day, has to put a terawatt, into the system, continuously. And the entire wind and solar fleet, worldwide, is just now getting to one terawatt and it's taken 30-40 years to get there.

We have to transition 20-30 terawatts! A terawatt is no joke. So, when I hear about projects that do one megawatt, that is addressing only a tiny fraction of one percent of the problem.

— Pathway 4 —

GREEN [ELECTRONS + FUELS + HEAT] + FOSSIL FUELS & CARBON CAPTURE

Making primary energy generation totally carbon-free is an essential goal for the energy economy of the future. However, much of the renewable energy technology and infrastructure is not currently ready to be deployed at the scales necessary to meet the accelerated decarbonization timeline the world must adopt to avoid the worst impacts of climate change. As we make this transition to a fully decarbonized grid, carbon capture technologies will be necessary to capture and sequester the carbon still being emitted by the fossil fuel industry in the meantime.

If and when the grid is as decarbonized as it can be, it is possible that renewable energy technologies and massive infrastructure upheavals may not be affordable for all economically vulnerable populations around the world. For these areas that will continue to rely on fossil fuels, carbon capture will still be critical in removing ongoing emissions, as well as the hundreds of gigatons of CO2 that humans have emitted into the atmosphere over centuries.

SOURCE

Technologies to cheaply capture CO2 from point sources (e.g. power plant exhaust) and direct air capture (DAC).

Electrification and synthetic chemical bonds noted in Pathways 1 & 2 and methods to harness geothermal heat in Pathway 3.

Note: In these scenarios, Carbon Capture Utilization & Storage (CCUS) is viewed as a "source" simply because it enables fossil sources to become cleaner. It does not imply that CCUS has to be co-located with fossil extraction or that oil and gas producers are directly responsible for bearing the costs of CCUS.

TRANSPORT

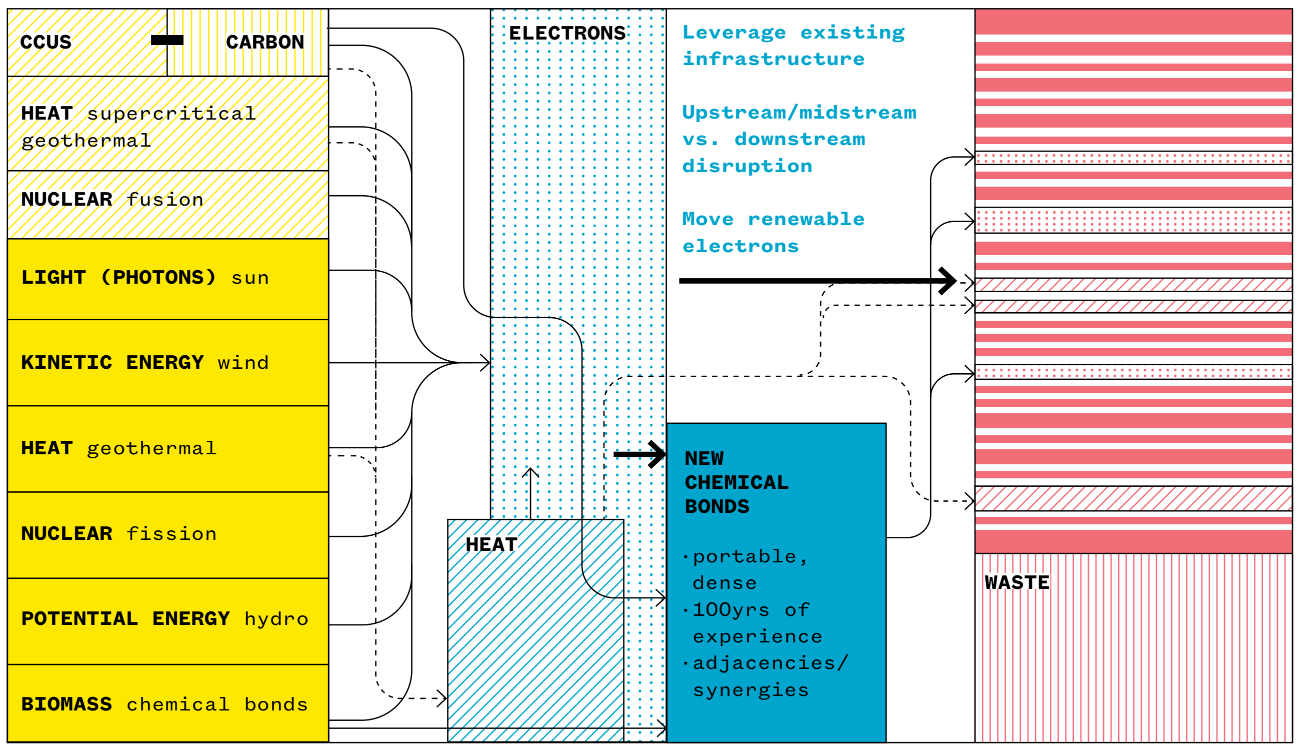
Utilize existing fossil infrastructure where possible. Additional infrastructure (e.g., pipelines) to transport captured CO2 to sequestration and end-use sites.

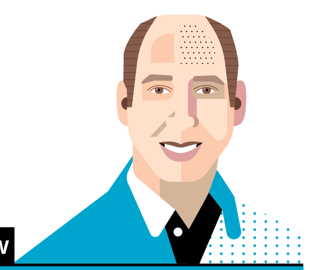
Transport solutions for electrons and synthetic chemical bonds noted in Pathways 1 & 2 and geothermal heat delivery in Pathway 3.

USE

Technology solutions to utilize captured CO2 as a carbon source for various end uses (e.g., liquid fuels, construction materials).

Phased electrification noted in Pathways 1 & 2 and retrofit solutions to utilize geothermal heat in Pathway 3.





Interview

PETER PSARRAS
Research Assistant Professor, Chemical and Biomolecular Engineering
University of Pennsylvania

Peter oversees the direction of Jennifer Wilcox's lab, focusing on CO2 removal and carbon capture. His research involves techno-economic and life-cycle assessments of CCUS and CO2 removal systems, specifically in identifying regional opportunities for deployment.

Many of those communicating revolutionary technologies, especially with regards to climate change, struggle with capturing the scale of the challenge. How do you put the work ahead into perspective?

When I talk about scale, it's about the rate at which we need to grow CCS (carbon capture and sequestration) processes — essentially an order of magnitude every decade. It helps to break it up like that, it translates our 2050 goals to what we must achieve today.

In terms of actual volumes of CO2 that need to be processed, I use the analogy of the growth in mobile phone popularity since the 1990s. Back then a mobile phone was a clunker, a luxury item, and now there are more than one per capita in the world. That's astonishing growth! That's basically the scaling that we need to do with CCS in terms of units of CO2 moved.

On the other hand, articulating the full scale of the challenge can quickly get terrifying and be viewed as putting the cart before the horse. As an example, I just helped the American Chemical Society do a video on CCS in which they were trying to calculate the amount of air that would need to be processed — and it is essentially half of the whole atmosphere.

To many, CO2 removal and carbon capture sound like the stuff of science fiction — can you talk about some of the most promising approaches and their significance?

We can look at what's actually been proven and what's been practiced for years — CO2 scrubbing and point source capture. It's always more efficient to go those routes (than direct air capture) — just block it from getting into the atmosphere in the first place. There are a lot of arguments about how appropriate or costly these approaches are, but none of those arguments, in my mind, is aligned with the state of climate emergency we find ourselves in. Think of it this way — your room is on fire; are you going to get out a whiteboard and argue about what window you're going to escape from?

Anything that plays on the Earth's natural carbon cycle is interesting to me. We study mineral carbonation in our lab, which is essentially an enhanced weathering process — you get capture and storage in one step and you obviate the need for most of the infrastructure associated with other approaches.

Which approaches excite you the most?

We've had promising ideas for many, many years, but there's never been a demand for CO2-derived products until now. We're seeing this ridiculous surge in demand. So much so, that in 5 or 10 years, we'll see a significant penetration of CO2-derived goods in the marketplace. But there are still barriers to adoption, especially with carbon storage — that approach is far more difficult than we anticipated, both technically and from a regulatory standpoint.

I have to mention Heirloom Carbon, co-founded by one of our students. Heirloom is commercializing a technology that enhances carbon mineralization, a natural geologic process, using natural and earth abundant minerals like alkaline oxides that can bind CO2 at ambient conditions. Careful engineering can enhance the kinetics from perhaps years to just days.

I was an author on California's Livermore Lab "Getting to Neutral" report from 2020; in it, you see waste biomass as a major component of the state's decarbonization initiatives. You see the same thing in Princeton's Net-Zero America report. Using waste biomass as a feedstock we can produce hydrogen and CO2. If the CO2 is stored away securely, the hydrogen has a negative carbon footprint and this opens the door to a number of potentially carbon neutral products using H2 and CO2 as co-feedstocks, like plastics or fuels.

What gives you hope?

The best minds are coming to the table to solve these challenges. And I've also seen a real shift to humanitarian elements, where for so long climate change was cast as an environmental problem. We're seeing many more people realize that this is our future — that our behavior directly impacts that future. All this, even in the face of an adversarial political climate, is hopeful. We've realized that we can't say "2050" like it's a million years away anymore. The practice round is over.

From a practical perspective, I am happy at the amount of scrutiny this space (CCS) is receiving. It makes it next to impossible for bad actors to continue with any type of market or regulatory manipulation. Meaning that we will get better data and better results with approaches that truly work.

Further reading:

- Cdrprimer.org
- Getting to Neutral: Options for Negative Carbon Emissions in California *https://bit.ly/getting_to_neutral*
- Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. *https://bit.ly/cost_of_DAC.* +

MAKING IT HAPPEN

A proposed timeline & the metrics that matter.

The pathways outlined above provide templates for how we might start visualizing a decarbonized energy ecosystem. However, the path each country, state, or community takes will depend on local resources, policies, costs, and several other factors. There will be no silver-bullet solution that fixes problems everywhere. Rather the energy system of the future will involve the complex interplay of several solutions working together and taking the local context into account across four key classes of metrics economic, spatial, social/political, and temporal factors.

Economics: Transitioning away from the status quo will require inventing and deploying new technologies at an unprecedented global scale. In addition to tackling the core innovation challenge, it will be important to ensure these new solutions are cost competitive with their more CO2-intense counterparts. This, in turn, will require establishing cost benchmarks for new technologies, allocating investments to pilots and engineering studies to explore/exploit economies of scale, and designing appropriate policy levers to align incentives.

In addition to managing costs relative to fossil counterparts, it is also important to note that low-income and economically disadvantaged communities around the world spend a significantly higher portion of their income on energy. As a result, some technologies may not be viable solutions for vulnerable populations due to affordability concerns and will require developing alternative solutions and policy support to enable wider adoption.

Specifically regarding pathway 4, major technological and political advancements will need to be made for carbon capture to become an economically viable technology. As the technology currently stands, the cost of capturing carbon from point sources is around \$53/t CO2 on average, while the cost of capturing carbon from DAC ranges from \$250-\$600/t CO2.[1,2] Tax incentives like the 45Q will (over the next 7 years) promise up to \$50/t CO2 captured for carbon that is permanently sequestered in underground geologic reservoirs.[3] This is a step in the right direction, but still not enough to make carbon capture an economically viable option as it stands right now. Major technological advancements that lower the cost of capture combined with continually more progressive tax incentives will be vital to the viability and much-needed implementation of carbon capture technologies.

Space: The transition to a no-CO2 energy landscape is also going to be a transition in the way we allocate and utilize land. The new technologies we deploy will vary in their demand for space, in the same way that countries around the world will vary in the availability of land (think Singapore vs the U.S.). Accounting for this supply-and-demand dynamic will be critical for matching and deploying the right technology set for a given geography.

Social/political: Ensuring reliable, cheap, and safe access to energy is critical to the socio-economic fabric of any economy. Managing a change in how we source and utilize energy on a global scale will inevitably lead to change across several social dimensions (e.g., skills, jobs, climate migration, energy poverty). While these issues may seem unrelated to technology at first, effectively managing managing and providing solutions to relieve them will be critical for the next generation of energy technologies.

Time: While countries may vary in their ability to pay for new technologies, availability of land and socioeconomic issues, the unifying challenge they all face is the compressed timeframe in which to combat the threat of climate change. As a result, of all the metrics relevant to the energy transition, the most important ones are the timescales related to development and deployment of new technologies.

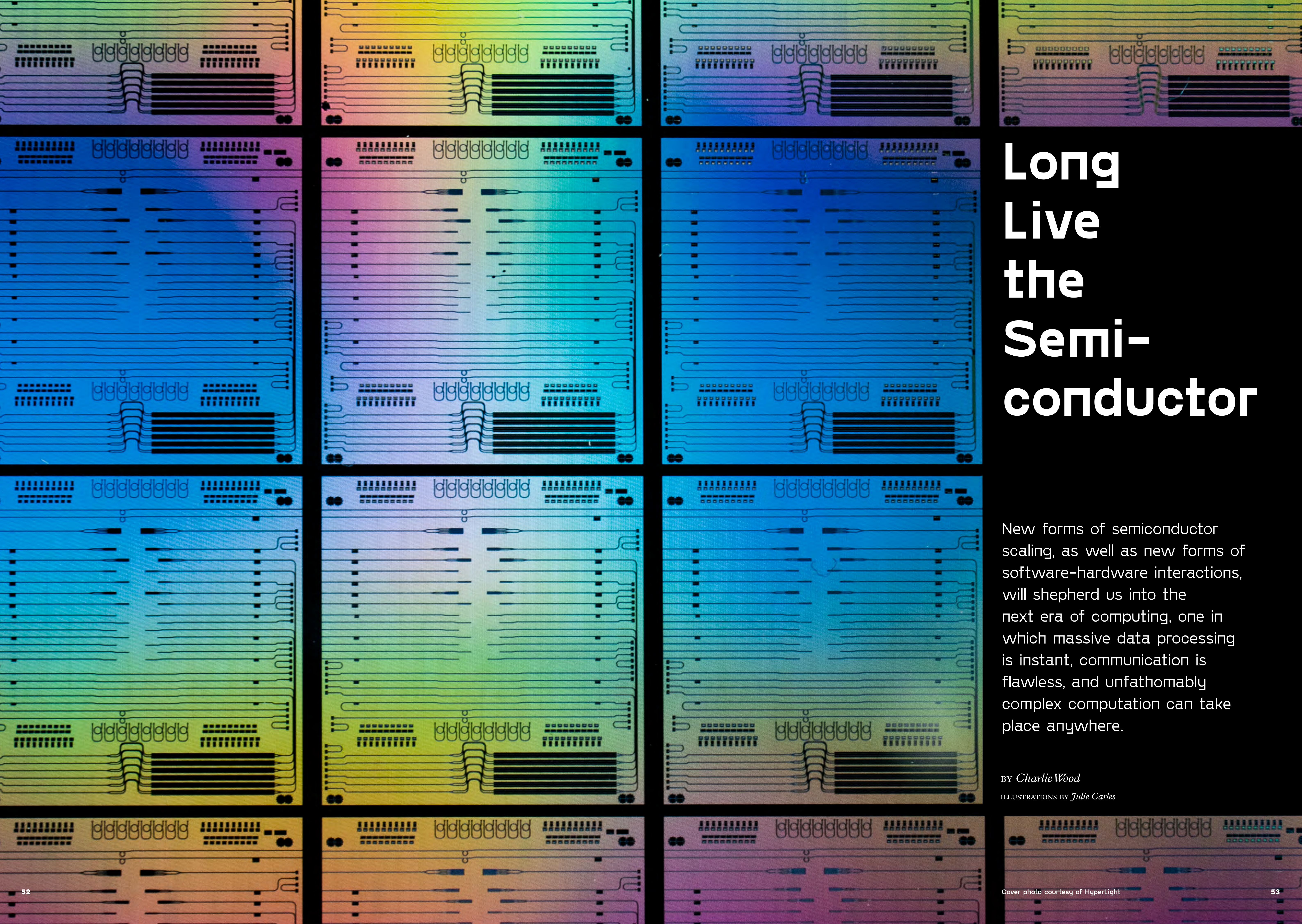
Learning rate is a commonly used metric to measure the development timescales of new technologies and is defined as the time taken to bring a technology to pre-defined scales and represents how quickly we can bring the economies of experience to bear on the costs of any given technology. Learning rates vary from technology to technology and depend on factors like capital intensity and policy support, both of which will be critical levers to go beyond traditional learning rates in the energy industry.

Deployment timescales also depend on capital intensity and policy support. However, an additional factor that can play a crucial role in our ability to deploy a technology is the timescale to train and develop the required skills in the workforce. Technologies that require skills that are readily available or require minimal retraining of the existing workforce will have a natural advantage in accelerating the deployment timescale. As new technologies reach maturity, it will become critical to anticipate potential talent bottlenecks and account for workforce development costs and timelines. Policy support and strategic partnerships between different players (e.g., start-ups, incumbents, national labs) will play a critical role in speeding up both the development and deployment timescales.+

(1) https://pubs.acs.org/doi/pdf/10.1021/acs.est.9b06147
(2) https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal
(3) https://carboncapturecoalition.org/45q-legislation/

The most recent IPCC report has provided much-needed perspective on the urgency of the climate crisis. With atmospheric CO2 levels at their highest concentration in over 2 million years, we are now looking at breaching the 1.5 °C threshold between 2030 and 2035. The need to commit to a decarbonization pathway has never been more urgent.

While the report makes it abundantly clear that human activity lies at the heart of the problem, humanity is also capable of rising to the challenge and finding the right solutions. The IPCC report itself, put together by 234 authors from 66 countries and capturing insights from >14,000 studies, is testament to what we can achieve when we put our collective minds to it. As you read this, millions of people across the spectrum of society — technologists, entrepreneurs, investors, policymakers — from all over the world are hard at work to bring the pathways above to reality. Their collective efforts are at once inspiring and hopeful — together, we will find a path to a cleaner CO2-free future.



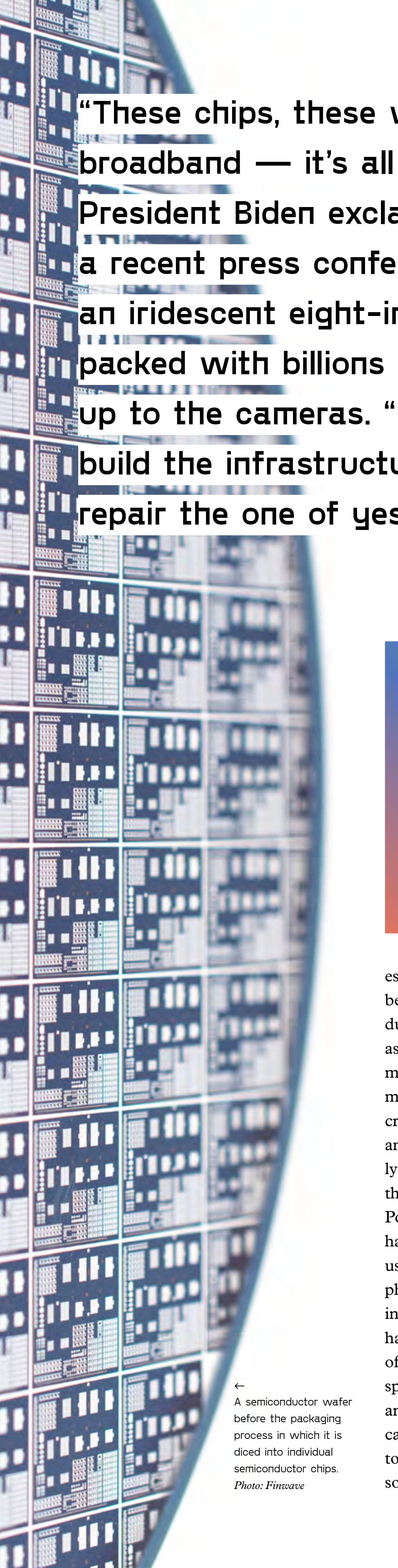
Long Live the Semi-conductor

New forms of semiconductor scaling, as well as new forms of software-hardware interactions, will shepherd us into the next era of computing, one in which massive data processing is instant, communication is flawless, and unfathomably complex computation can take place anywhere.

BY *Charlie Wood*

ILLUSTRATIONS BY *Julie Carles*

Cover photo courtesy of HyperLight



← A semiconductor wafer before the packaging process in which it is diced into individual semiconductor chips. *Photo: Fimwave*

"These chips, these wafers, batteries, broadband — it's all infrastructure," President Biden exclaimed during a recent press conference, holding an iridescent eight-inch silicon disk packed with billions of transistors up to the cameras. "We need to build the infrastructure of today, not repair the one of yesterday."

Despite being largely invisible and embedded within our devices, semiconductors now form a system as essential as roads or the electrical grid. So many facets of our daily lives — not to mention our future prospects — rely critically on these glimmering objects, and the streams of electrons alternately passing and not passing through their unimaginably thin channels. Pocket-dwelling supercomputers have granted us superpowers, letting us hail cars, identify music, and take photographs sharpened by artificial intelligence. Computational prowess has also advanced our understanding of the world, giving us models of how space quivers when black holes collide and more accurate forecasts of a hurricane's course. Whether we will be able to keep expanding this arsenal of awesome powers at the same clip depends largely on semiconductor technology, a half-trillion-dollar industry that still remains obscure to the average person.

For decades, titans such as Intel and IBM have fashioned computer chips from ever smaller elements, spawning jumps in computation along with drops in price at such regular intervals that the progress became not just an expectation but a law, Moore's Law. Today's computer chips boast many millions of times the power of those 50 years ago. The processor inside even the brick that charges your phone has hundreds of times the power of the Apollo 11 Moon Landing Guidance computer, to say nothing of your phone itself. In the last decade, however, the progress of all-purpose processors has staggered as their silicon parts have shrunk so much that manufacturers are nearly working with individual atoms. At the same time, the appetite for handling 0's and 1's is exploding, with scientific institutions and businesses alike seeking more answers in bigger datasets. Researchers fear that the tsunami of computational need may swamp the abilities of machines, stymieing progress.

"It will stop innovation," says Jeff Chou, an electrical engineer and founder of Sync Computing, a startup attempting to accelerate cloud calculations. "It will be a cap on what we can do."

As this impasse draws closer, it puts more pressure on researchers and entrepreneurs to come up with ways to save computing — ways to reinvent it. As a result, more and more of Silicon Valley's famous venture capital has been flowing into semiconductors, an industry that has in the last two decades often been considered too capital intensive to compete with, for instance, software. While building a bleeding-edge foundry has never been tougher, hiring an existing foundry to produce a bespoke chip has never been easier, and investors are flocking to startups creating processors tailored to artificial intelligence and other lucrative applications.

The federal government is also getting involved. Recognizing the strategic value of producing this essential infrastructure domestically, Biden's infrastructure plan calls on Congress to invest tens of billions of dollars to reboot the U.S. semiconductor fabrication capacity. Much of that funding would go into traditional silicon fabrication, supporting innovators hoping not just to revive Moore's Law but to surpass it.

There is no single replacement for the silicon transistor; nor is there just one bottleneck to resolve. If society is to continue to enjoy the rapid progress that has defined the information age, we will have to find more efficient ways to work with the processors we have, new processors tailored to the hardest calculations we face, and new materials for novel chips that can help processors communicate more quickly. Semiconductors play many roles in the informational ecosystem, and all of them are ripe for reinvention.

"People are realizing that we're reaching the limit of where we can get to with the hardware," says Owen Lozman, an investor with EMD Electronics's investment arm, M Ventures. "We need a paradigm shift."

A 50-YEAR RACE TO THE BOTTOM

In 1959, Nobel physicist Richard Feynman gave a lecture at the annual meeting of the American Physical Society entitled, "There's Plenty of Room at the Bottom." The computers of the era were hulking machines that took up entire rooms in our macroscopic world — "the top," in Feynman's way of thinking. Instead, he urged engineers to explore "the bottom," the miniature world of molecules and atoms. If these particles could become the building blocks of sub-microscopic transistors, computers could dramatically shrink in size while growing in power.

"Computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements – and by little, I mean *little,*" Feynman said. "The wires should be 10 or 100 atoms in diameter."[1]

Just six years later, Gordon Moore, a semiconductor researcher who would go on to co-found Intel, wrote an essay observing that the race to the bottom had already begun. He noted that the most economical number of components to carve into an integrated circuit hovered at around 50, but that the figure was doubling every two years, a forecast that became known as Moore's Law.[2]

The law has various incarnations relating to power, price, and energy, but in practice, the trend's main driver has been the shrinking of the element at the heart of modern computing: the semiconductor transistor, an electrical switch that flickers on and off with no moving parts.

While early electronics were based on vacuum tubes — airless bulbs with a wire that could produce an on-demand stream of electrons when heated — the modern computing era began in the 1950s with the invention of the silicon transistor. On the atomic level, insulators hold their outer electrons tightly while conductors let them roam free. Semiconductors fall in the middle. Their atoms keep their electrons loosely tethered, so an applied electric field can liberate them.

This property let researchers engineer electric valves out of solid silicon blocks that could switch between the open and closed positions much more quickly, using far less energy than vacuum tubes. Crucially, making continually smaller patterns of silicon was much easier than shrinking complicated bulbs, creating a long runway for companies to take up Feynman's challenge.

JEFF CHOU
CEO & Co-Founder, Sync Computing

OWEN LOZMAN
Managing Director, M Ventures

The semiconductor industry delivered, developing a complex international supply chain dedicated to transmuting piles of sand (a plentiful source of silicon) into the most intricately crafted devices in existence, with modern semiconductor chips packing in billions of transistors each measuring just dozens of nanometers across — so small that it would take more than 200 to cross a red blood cell. In 1965, Moore forecast that chips would someday host as many as 65,000 components. Last year, Apple shipped iPhones with processors containing 11.8 billion transistors.

In 1965, Moore forecast that chips would someday host as many as 65,000 components. Last year, Apple shipped iPhones with processors containing 11.8 billion transistors.

(1) https://www.zyvex.com/nanotech/feynman.html
(2) https://newsroom.intel.com/wp-content/uploads/sites/11/2018/05/moores-law-electronics.pdf

MUKESH KHARE
Vice President,
Hybrid Cloud, IBM Research

NEIL THOMPSON
Innovation Scholar,
MIT CSAIL

But room at the bottom, in the atomic realm, is running out.

Modern chip manufacturers use light beams as scalpels to hew minuscule components, a booming business.

And next-generation chip production currently hinges on one machine, from one company, that can produce an exact enough light blade. Dutch multinational ASML has developed the only technology that can harness extreme ultraviolet light (EUV). To produce the 13.5 nanometer-wide ripples of light, ASML uses pulses from a metal-cutting laser to vaporize microscopic droplets of molten tin 50,000 times each second. At those wavelengths (which are more than a dozen times finer than the industry-standard ultraviolet light), even air blocks light, so the entire process takes place in a vacuum. ASML makes a few dozen EUV machines annually, each of which weighs 180 tons, takes four months to build and costs more than 150 million dollars. ASML's market capitalization has grown from about $47 billion five years ago, to nearly a third of a trillion dollars today.[3]

That's not to say there's no progress at the bottom. The Taiwan Semiconductor Manufacturing Company (TSMC) has commercialized ASML's EUV machine to produce Apple's A14 iPhone chip, and the tool is an essential part of the roadmaps of Samsung, Intel, and IBM. Earlier this year, IBM unveiled a chip produced with what it calls "two-nanometer" technology.[4] The transistors themselves aren't so much smaller than previous generations, varying from 15 to 70 nanometers in length, but IBM harnessed EUV manufacturing and other innovations to stack transistors for greater electrical control, packing 50 billion components into a fingernail-sized chip for a density 3.5 times greater than what current so-called "seven-nanometer" processes can achieve.

But the industry can afford only so many advances of this type. Dozens of chip manufacturers have quit the race to the bottom since 2002, squeezed out by prohibitive prices (Intel is spending 20 billion dollars on two new foundries).[5] And the few that remain are starting to band together. ASML's EUV technology is the result of a decades-old private-public consortium and funding from Intel, Samsung, and TSMC. Despite these efforts, the companies are getting less and less bang for more and more bucks. On one benchmark (known as SPECint), single-core microprocessor performance improved by 50% each year in the early 2000s, but by only 4% between 2015 and 2018. (The rise of multi-core processors came about in part to compensate for this performance plateau.)[6]

"While Moore's law is slowing down, we do know there's a pathway for innovation," says Mukesh Khare, Vice President at IBM Research. "Tech scaling isn't only about miniaturization," he continues, pointing to the rise in specialized computing components as an alternative way to keep powering up chips.

Yet even as Moore's law falters, the world has never needed it more. An explosion in software services has led to an exponential hunger for computing power. Software companies are increasingly outsourcing their calculations to cloud service providers. This chip rental business generated more than 120 billion dollars in revenue in 2020, a roughly 100-fold increase from 2010.[7] And the number of calculations needed to train the most sophisticated artificial intelligence programs (such as DeepMind's championship-winning AlphaGo Zero) surged by more than 300,000 times between 2012 and 2018, far outstripping any version of Moore's law.

If demand for computing capacity continues to outpace supply, the era of cheap computing could soon come to an end. Some software companies already spend half their revenue on cloud services, and data centers consume more than one percent of the world's energy.[8] Researchers and companies once scaled up their enterprises by doing more of their computing at the seemingly endless bottom. But now that expansion is shifting to the top, where companies are building bigger data centers and recruiting more chips at an increasingly high financial and environmental price.

"A lot of the benefits that came from Moore's law; actually many of those things have already disappeared," says Neil Thompson, an economist at MIT's Computer Science and Artificial Intelligence Lab.

Modern necessities like affordable calculation will continue to disappear as the bottom fills up — unless, that is, electrical engineers and computer scientists can make room somewhere else.

SMARTER CALCULATIONS

One of Feynman's 1959 predictions was that more capable machines would streamline their own computations. "They would have time to calculate what is the best way to make the calculation that they are about to make," he said.

Jeff Chou and Suraj Bramhavar are two engineers on their way to realizing a variation of this vision with an entirely different form of computing.

Almost all computers answer queries by flipping transistors on and off in such a way that they execute binary calculations in an order specified by a program: first do this, then do that. But this paradigm is not the only way to calculate.

Nature also computes. Cannonballs trace out parabolic trajectories; light always finds the quickest route between two points. The universe will always seek out the path of least resistance. Such thinking drives the development of some quantum devices, which leverage the bizarre physical behavior of particles in ways that are impossible to capture with 0's and 1's.

Or you might use a classical, but not digital, device known as an analog computer — a machine that physically acts like the specific system you want to study. After meeting at MIT's Lincoln Laboratory, Chou and Bramhavar developed precisely such a machine using electric currents that synched up in a particular way.

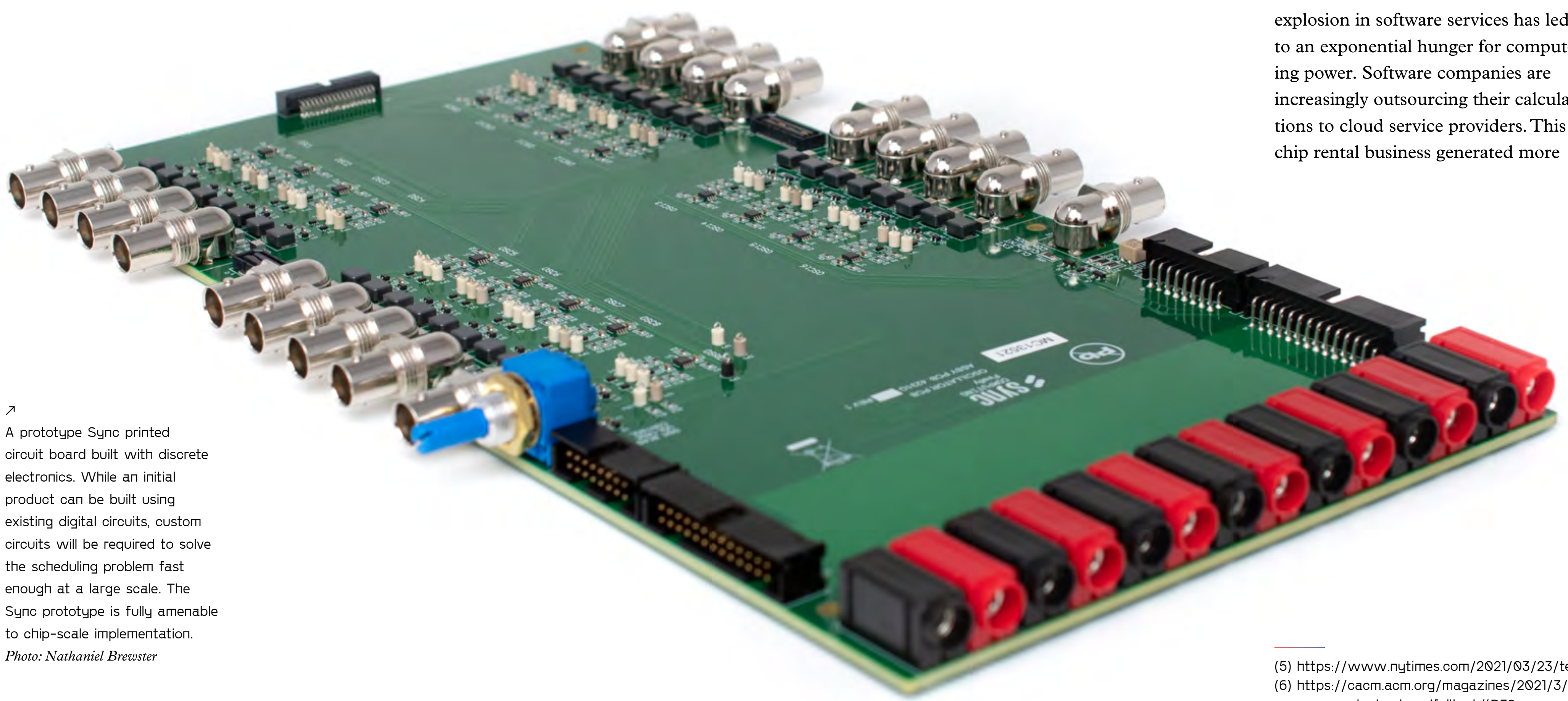
"We built this very cheap 20-dollar circuit that could basically do the same thing that a lot of quantum companies are trying to do," Chou says. Their research was published in Nature's *Scientific Reports.*

Their circuit solved a particular class of math problem known as combinatorial optimization, essentially searching an exhaustive list of possibilities for some ideal solution. One example is the traveling salesman problem, where a salesperson seeks the fastest route between cities on a map. With each additional city, the number of routes the salesperson must check grows exponentially.

This is a problem that logistics organizations like USPS and FedEx tackle daily. It's also a crucial aspect of cloud computing, Chou and Bramhavar realized, where bits of information flow back and forth between staggering numbers of computer chips in data centers.

"You're trying to send a bunch of different computing jobs to a bunch of different computers at the right time at the right place," Bramhavar says. "How do you make 1,000 chips work together better, or 10,000 chips, or 100,000 chips?"

The duo started by developing software that could mimic the behavior of their physical circuit while running



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A prototype Sync printed circuit board built with discrete electronics. While an initial product can be built using existing digital circuits, custom circuits will be required to solve the scheduling problem fast enough at a large scale. The Sync prototype is fully amenable to chip-scale implementation.
Photo: Nathaniel Brewster

(3) https://ycharts.com/companies/ASML/market_cap
(4) https://newsroom.ibm.com/2021-05-06-IBM-Unveils-Worlds-First-2-Nanometer-Chip-Technology,-Opening-a-New-Frontier-for-Semiconductors

(5) https://www.nytimes.com/2021/03/23/technology/intel-arizona-chip-factories.html
(6) https://cacm.acm.org/magazines/2021/3/250710-the-decline-of-computers-as-a-general-purpose-technology/fulltext#R32
(7) https://www.srgresearch.com/articles/2020-the-year-that-cloud-service-revenues-finally-dwarfed-enterprise-spending-on-data-centers
(8) https://www.wired.com/story/data-centers-not-devouring-planet-electricity-yet/

JOHN KELLY

EVP of IBM, Retired
Special Advisor to Chairman and CEO, IBM

For over 40 years, Dr. John E. Kelly III has played numerous significant technical and business roles driving IBM's leadership in technologies ranging from semiconductors to supercomputers to Artificial Intelligence (AI) cognitive systems. He and his team were responsible for advancing the science of AI and cognitive computing through his support for Watson, the groundbreaking system that defeated two standing Jeopardy! world champions in 2011.
Dr. Kelly is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), and a member of the National Academy of Engineering. He is a member of the Board and a former Chairman of the Semiconductor Industry Association. He also is a member of the Boards of Trustees for Union College and RPI.

There was a fascinating concept articulated by Rafael Reif, the President of MIT, during an event for the University's College of Computing — the notion that the "future is algorithmic. Do you agree? I would love to hear your thoughts on the future of computing and communication, specifically the interplay between software and hardware.

Those who think that things are going to slow down or stop are not correct. They're looking at it in terms of traditional Moore's law — the concept of horizontal scaling. And they're thinking in terms of the traditional hardware and software that we built over the past 60 years. If you look at it only through the rearview mirror, you could convince yourself that the world's technology and computing is slowing down. But what excites me are new forms of scaling and new forms of hardware/software interactions. Here are three that I think will be vital to our future:

- While 2D-scaling is getting really, really tough, 3D-integration is just blossoming. From stacking transistors and devices to stacking chips and advanced packaging technology. — 3D integration is the future.
- Heterogeneous computing and optimization (this is both a hardware and software statement) is advancing rapidly. In the past, compute has been mostly homogeneous, take microprocessors for example. You have a chip and put an operating system on top. What we're seeing now is hardware tailored for certain workloads. Many talk about video game hardware (GPU's) and its use in AI, but there are all kinds of accelerators for databases and other aspects of computing. It's no longer a world of a simple CPU, memory, and I/O. This heterogeneity also means that software must adapt to the underlying heterogeneous hardware.
- There's tremendous innovation going on in AI optimization at both the hardware and software layers. Data's growing exponentially, but it's not about just computing with that data. It's about gaining insights from that data. And the best and fastest way to do that is through the use of AI. The most energy-efficient way to do that is through AI-optimized hardware and software.

How will innovations in these areas impact our daily lives?

There's a reason that your iPhone is so small and so compact. If you were to open it up and look inside you'd see 3D packaging — stacked, energy-efficient chips. And this is just the beginning of 3D integration and heterogeneous optimization!

The two biggest computers in the United States are a system at Lawrence Livermore National Labs and one at Oak Ridge, they are several hundred petaflops, and they're heterogeneous — a combination of IBM CPUs and Nvidia GPUs. These systems are helping solve massive challenges like drug discovery and climate change.

There are hundreds, perhaps thousands, of startups making AI-optimized software and hardware. There is significant innovation in that space. Can you imagine how these companies will change cloud computing? You're going to have one hell of a smartphone.

We've seen massive consolidation in the semiconductor industry, and there are rumors of even more. What does this mean for innovation in the sector? And what does it mean for the fate of semiconductor startups?

Such industry consolidation is natural. Many consolidations happen because the chip companies want to supply more of the heterogeneous stack. That doesn't mean that there will not be tremendous innovation — there will be.

There will also be new degrees of freedom for startups. Like I mentioned before, this is the time of heterogeneous optimization and 3D integration. Let's say you invented the world's best AI accelerator. You do not have to be integrated into a giant CPU with Intel or IBM. You can be integrated into a module alongside one of those CPUs. There's substantial interest in these startups from within the VC community — we're seeing a resurgence of investments in chip and software technologies.

Is national semiconductor policy proceeding as you predicted? What's next for the policy and the industry?

Yes, I've been really pleased with how the policy is proceeding. The CHIPS Act was passed in the Senate by a great majority and is now in the House. The speaker has said that it should get through shortly and then it will be on the President's desk. While that's been going on, we in the industry have been working together on how to most effectively use this money for innovation in the United States. And we're ready to go, immediately. I am thrilled that the U.S. government has established an industrial policy for the semiconductor industry.

As for the future of the sector? It's an exciting time, but we cannot realize its potential without a vibrant workforce. We are going to need to train hundreds of thousands of people in manufacturing all the way up to PhDs and postdocs. We cannot let the CHIPS Act be a one shot deal. We must put the processes in place to support the industry for generations. We must redouble our support of electrical engineering education and the associated research.

remotely on Amazon Web Services (AWS) and founded Sync Computing to commercialize the technology. Early collaborators included NASA and the Air Force, who helped speed up simulations of aircraft performance by 30 to 40 percent.

Now they've moved on to more advanced versions of the scheduling algorithm, which helps clients from retailers to restaurants reduce their ballooning AWS cloud bills. The gains vary, but the algorithm has sped up jobs by 20 times. "It just shows you [all] the potential waste," Chou says.

The group started out using their algorithm to orchestrate the flow of information between cores on a single chip. Now, they coordinate informational traffic between different racks in a data center. Eventually, they hope to come full circle and design an enterprise version of the original 20-dollar circuit to dispatch jobs between data centers.

"That problem gets so large that you can't solve it quickly enough with software, and you need hardware," Bramhavar says. "That's where our long-term vision comes in."

USING LIGHT TO GO BIG

Building huge, datacenter-like computers is a strategy Feynman considered too, although he advocated for "the bottom" to avoid the physical limits of "the top."

"If we wanted to make a computer that had all these marvelous extra qualitative abilities, we would have to make it, perhaps, the size of the Pentagon," he said. But "the computer would be limited to a certain speed," he continued, since "the information cannot go any faster than [that]."

Each of the two largest U.S. data centers already cover nearly one-sixth of the geographic footprint of the Pentagon — the world's largest office building — and indeed much of the information inside them flies through fiber optic cables at close to light speed.[9] But as data centers have grown, a more significant choke point has emerged. Light is fast enough, but converting the light into and out of the sluggish streams of electrons that silicon chips use to calculate takes time.

"The best medium to compute is electrical signals. The best medium

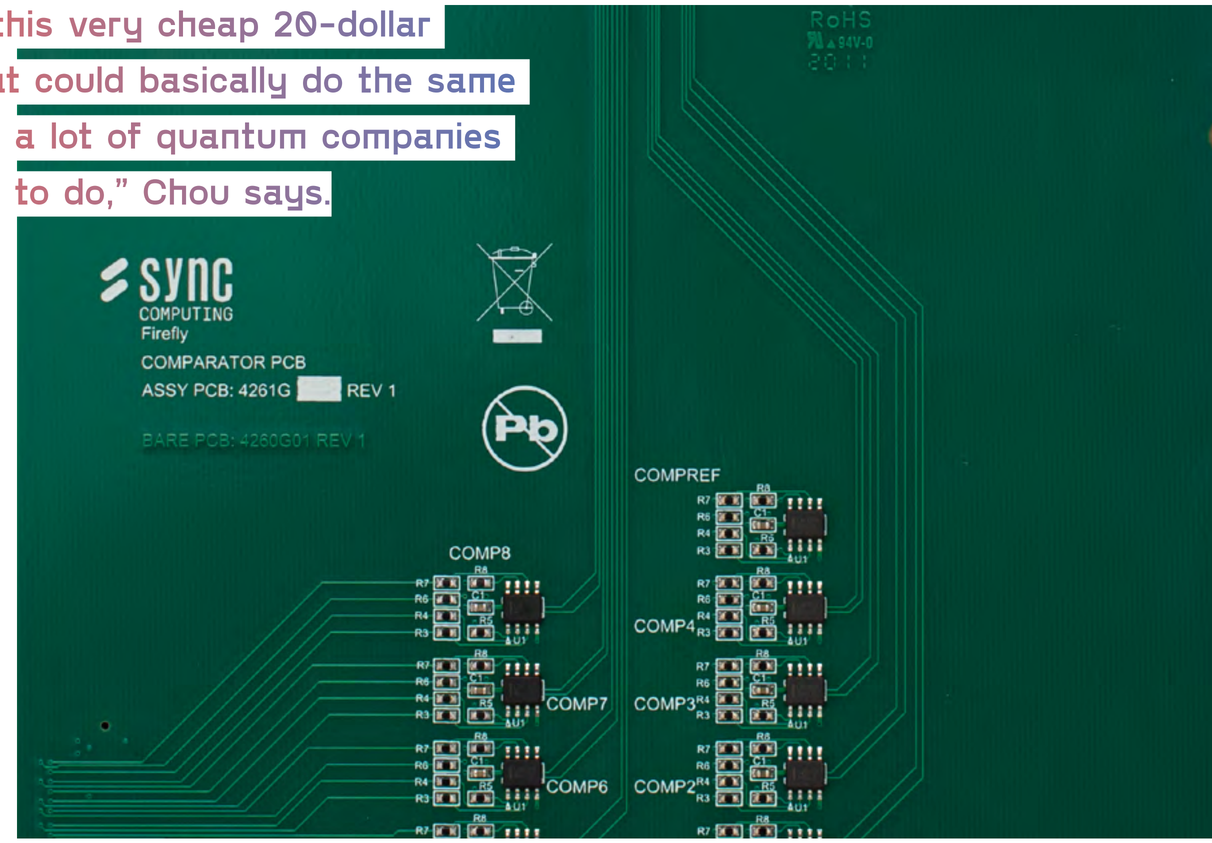
SURAJ BRAMHAVAR

CTO & Co-Founder,
Sync Computing

MIAN ZHANG

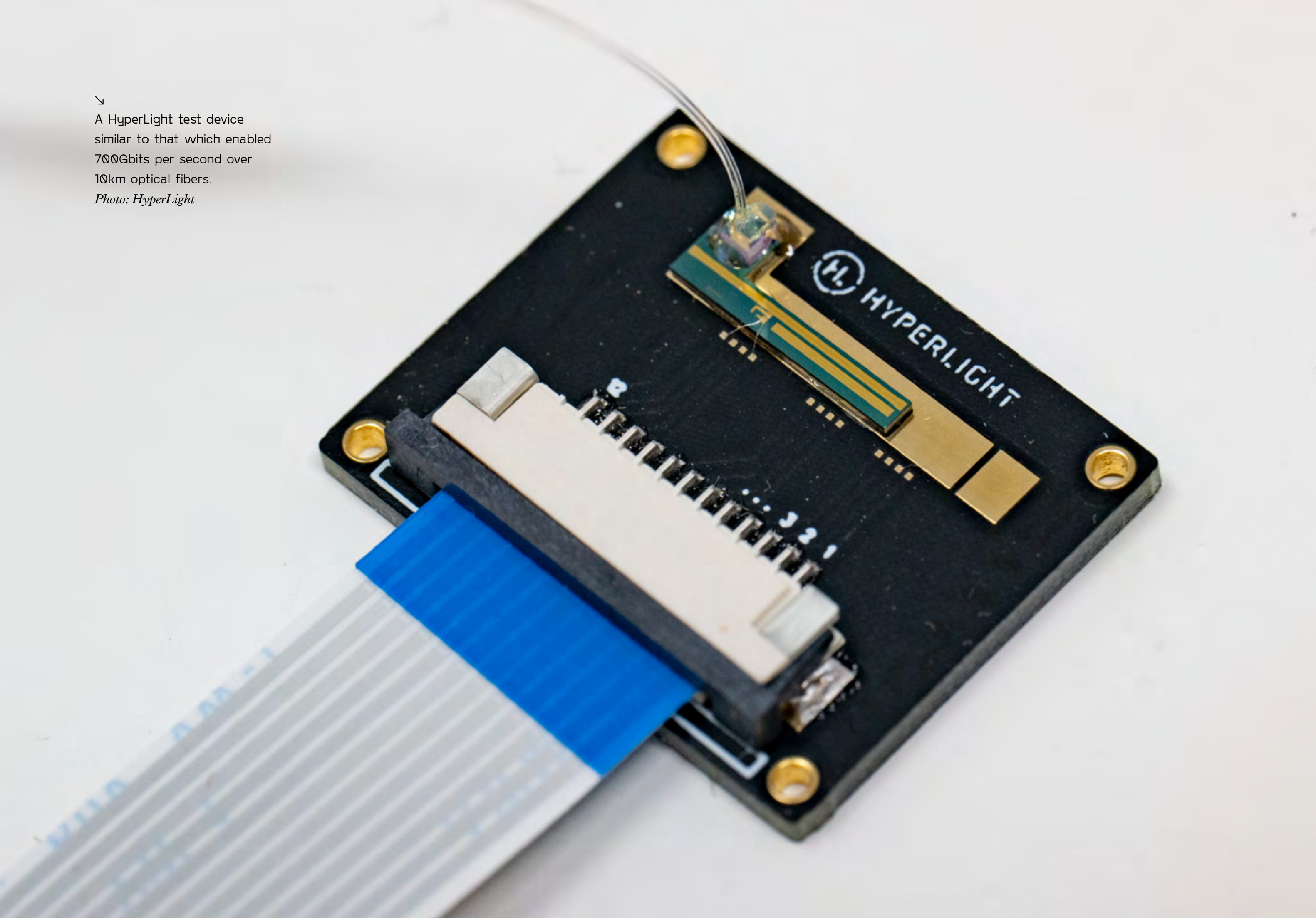
CEO & Founder,
HyperLight

"We built this very cheap 20-dollar circuit that could basically do the same thing that a lot of quantum companies are trying to do," Chou says.



→ A prototype Sync printed circuit board built with discrete electronics.
Photo: Nathaniel Brewster

(9) http://worldstopdatacenters.com/americas-size-rankings/



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A HyperLight test device similar to that which enabled 700Gbits per second over 10km optical fibers.
Photo: HyperLight

to communicate is optical signals. So you see where this problem is," says Mian Zhang, a photonics researcher and CEO of HyperLight, a company attempting to break this bottleneck.

Zhang, an engineer by training, never expected to co-found an integrated photonics company. But after his postdoctoral work at Harvard developing a new type of photonics conversion chip led to a series of *Nature* papers in 2018 and 2019, he received an overwhelming response from investors.

"We got very serious people interested," Zhang says. "Instead of saying, 'Hey this a nice scientific discovery,' they were saying, 'Where can I get these chips?'"

Some large data centers today have millions of integrated circuits devoted to translating information between photons and electrons. These chips are typically made from silicon, due to the semiconductor industry's prowess at shaping that material. But the element does not respond naturally to light. Manufacturers must infuse it with other atoms to change its properties, which has the inconvenient side effect of making the silicon opaque to the very light it should transform.

This drawback has opened the door for other materials: notably, a transparent salt known as lithium niobate, whose crystal structure warps as light passes through it. Changes in the atomic structure tell the electrons how to move, allowing information to pass between the two worlds. Moreover, lithium niobate can deform itself hundreds of billions of times each second, fast enough to keep up with modern communication.

Zhang and his colleagues discovered a way to get the best of both worlds, harnessing the honed technology of semiconductor foundries to chisel thin films of lithium niobate. Their devices have set multiple world records. In December 2020, HyperLight demonstrated a conversion rate suitable for use within data centers that was seven times faster than what silicon-devices on the market today can handle.[10] And in March 2021, they achieved breakthrough voltage-bandwidth performances in integrated electro-optic modulators. Those speeds should satisfy the growing hunger for data transmission for another decade, Zhang estimates, enabling collective computing on a scale that dwarfs the Pentagon. "All the different racks are going to behave like a single machine," he says. "Data centers around the world are going to behave together like a mastermind."

LOW POWER & HIGH EFFICIENCY

Feynman foresaw another barrier to computation's expansion at the top: mammoth facilities would drain the electric grid. "There is also the problem of heat generation and power consumption; TVA [the Tennessee Valley Authority] would be needed to run the computer," he told his audience at the California Institute of Technology.

His forecast was overly pessimistic but not entirely off. Data centers have held their energy consumption steady in recent years thanks to innovations in extreme efficiency, but researchers predict that they won't be able to keep up with the growing appetite for calculations. By 2030, information and communications technologies may consume a fifth of global electricity.[11] And many of those watts won't even make it into chips to do work. More than 60 percent of power is lost between generation and use, according to Tomás Palacios, an MIT professor and engineer. Resistance in power lines saps energy during transmission, for instance. And after the current comes out of the wall, it passes through power adaptors and other power electronics that repeatedly reduce the voltage to what a device's processor can handle, wasting energy at each step.

To reduce power consumption and enable other game-changing technologies, Palacios believes the semiconductor industry needs to look beyond its favorite one-size-fits-all material.

"The future of society is all about managing energy, information, and communication," he says.

Silicon excels at manipulating information but "is not very good for the other two pillars."

Palacios co-founded Finwave Semiconductors with Bin Lu, another MIT engineer, to bring a new semiconductor into the fold: gallium nitride, or "GaN."

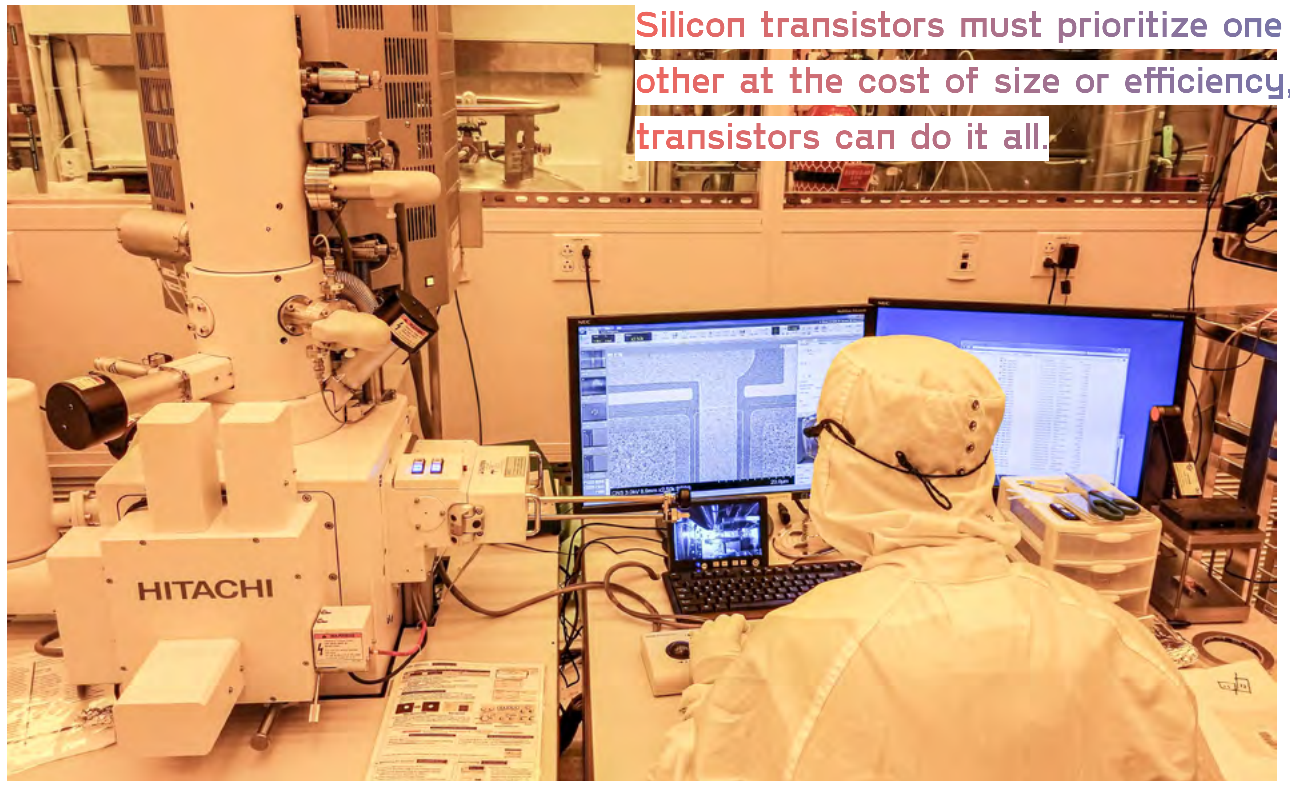
Semiconductors enable electric switches because they hold onto their electrons loosely enough that the particles can be freed on demand. GaN, however, is an example of a material that won't give up its electrons without a fight — a "wide bandgap" semiconductor. Compared with silicon, GaN transistors need a more energetic electric field to open and close, letting them handle higher voltages and switch states more frequently. Silicon transistors must prioritize one or the other at the cost of size or efficiency, but GaN transistors can do it all.

"For the future of power electronics, you need high frequency and high voltages," Palacios says. "Wide bandgap semiconductors are the only materials that can give you both."

TOMÁS PALACIOS
Professor of Electrical Engineering & Computer Science, MIT

BIN LU
CEO & Co-Founder, Finwave

Silicon transistors must prioritize one or the other at the cost of size or efficiency, but GaN transistors can do it all.



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The Finwave team at work in a foundry, prototyping its GaN transistors.
Photo: Finwave

(10) https://www.businesswire.com/news/home/20201214005049/en/New-Data-Rate-Record-for-Intensity-Modulated-Single-Wavelength

(11) https://www.nature.com/articles/d41586-018-06610-y

JEAN LUIS MALINGE

Venture Partner, ARCH Venture Partners

SUBAL SAHNI

Senior Director, Photonics Engineering, Celestial AI

MICHELLE TOMASKO

VP of Software & Co-Founder, Celestial AI

Finwave will soon release a 650-volt GaN transistor that could help data centers save energy, but the company is really aiming to disrupt Palacios's third pillar: communication.

Beaming information through the air amounts to another conversion of power, from electricity into microwaves. Here, GaN's greater efficiency and higher frequency pay off in the form of ten times higher outpower for base stations and up to four times better battery life for handheld devices. The 5G infrastructure rolling out today operates at relatively low frequencies, but GaN transistors could catalyze a faster, "millimeter wave" communications network.

"We have a unique technology no one else has," Lu says. It "has a chance to truly enable revolutionary millimeter wave 5G."

STARTING A NEW RACE

One trend Feynman did not anticipate in 1959 was that once computing hit the bottom it, might strike out in a new direction entirely. We already use light to move data between continents and cities, and recently between server racks in some data centers. For decades, streams of light laden with information have inched steadily closer to where the real action is happening: the motherboard.

"We are at the point where it's starting to penetrate the box," says Jean-Louis Malinge, an engineer and investor who has worked with photonics in telecommunications for 30 years. "The photons are progressively replacing the electrons."

A universal computer based entirely on light remains a distant dream, but a handful of companies are taking the first steps toward bringing photons into the heart of the computational ecosystem with hybrid processors outsourcing specialized, arduous work to photons.

"Photonics computing has been this holy grail type thing for decades," says Subal Sahni, Director of Photonics Engineering at Celestial AI. "[Moving and manipulating electrons] is expensive due to power dissipation in chips. For light, it's pretty much free."

Startups like Celestial AI are building chips that will take advantage of light's properties for one specific application: machine learning.

When computer scientists first attempted to run machine learning algorithms on the computers of the 1950s, the machines just weren't up to the challenge. Training neural networks to do useful tasks boils down to multiplying gigantic matrices. Doing so sequentially with a rudimentary CPU was a bit like asking a third grader to multiply interminable numbers by hand.

We owe the recent machine learning renaissance to the rapid development of Graphics Processor Units (GPUs), which run slower than CPUs overall but can execute hundreds to thousands of multiple operations simultaneously. Today, GPUs are also running out of room at the bottom.

Hybrid photonics chips, however, could be multiplication heroes. To multiply with light, Sahni explains, you simply write a variable into a light beam (in the normal way you might encode a Netflix video) and then modulate the beam a second time to calculate. In this way, the process condenses a tedious multiplication into a single step.

All manipulation of the light takes place in silicon (which is transparent at telecom photon frequencies), where features like groves and fins guide and shape the beams. Many world-class semiconductor foundries, including Intel and TSMC, can already carve increasingly sophisticated photonics circuits into silicon.

A handful of companies are taking the first steps toward bringing photons into the heart of the computational ecosystem with hybrid processors outsourcing specialized, arduous work to photons.

Imagining what future engineers will build with advanced versions of today's rudimentary technologies is a bit like asking a young Moore to speculate about what people might do with billions of transistors in their pockets.

Celestial AI is operating in stealth mode, and its founders couldn't describe the design or abilities of its machine learning chip. But the company's founders feel confident that hybrid photonics can restore the explosive computational growth society has come to expect.

"It can have the same exponential pace of improvement generation over generation that we have historically enjoyed with Moore's Law," says Michelle Tomasko, one of Celestial AI's co-founders and its head of software. "We start at a big pop and go exponential from there."

FUNDING THE FUTURE

The silicon industry now stands at a crossroads. Deep-pocketed giants like Intel and IBM will likely inch closer to the bottom, but 55 years of Moore's Law has essentially perfected the silicon transistor.

"It worked really well for many decades." says Palacios. "We are now at the point where we need another push."

That push may come from the federal government, which has been considering a substantial investment in semiconductor technologies, initially in the form of the bipartisan $37-billion American Foundries Act (AFA) and the Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act in 2020.[12] This spring, Biden asked Congress to expand the semiconductor investment to more than $50 billion as part of his infrastructure plan, and in June the Senate adopted many of the key propositions in its United States Innovation and Competition Act.[13] The initiative aims to recapture semiconductor manufacturing market share, more than 70% of which has shifted to Taiwan and South Korea, and to help the United States keep its status as a global leader in cutting-edge technologies like AI and supercomputing, even as China endeavors to displace it.[14,15]

By building local manufacturing capacity for silicon while supporting emerging technologies, the program could help labs and startups introduce new paradigms like analog computing, GaN transistors, and photonics into the wild even sooner.

"This has the potential to really change the world," Palacios says, "in the same way that the Apollo program opened the space age."

The transformation would be profound. Today's watches clock our heartbeats, but tomorrow's wearables could monitor much more. Apple has invested $70 million into Rockley Photonics, a UK-based company developing a "clinic-on-the-wrist" sensor that tracks blood oxygen, glucose, alcohol, and more — using light.[16] Related photonics technology may shrink LiDAR, improving the eyesight of self-driving cars. Australia's "Sydney Harbor Bridge" already hosts 2,400 sensors, which report vibrations to machine learning algorithms that look for signs of an impending catastrophe.[17] And this is just the beginning of the possibilities enabled by the convergence of power sipping circuits, lightning-fast wireless communication, and artificial intelligence to process it all.

"These are just proof-of-concepts we're seeing at the moment," Lozman says.

"In the coming decades, purpose-built chips matched to their application could slip into everything from appliances to clothing, literally weaving computation into the fabric of daily life. Screens will melt away as windows display the weather forecast and devices beam holograms into the air. Algorithms may even design the next generation of AI-boosting chips, accelerating the acceleration."

Or perhaps something entirely different will come to pass. Imagining what future engineers will build with advanced versions of today's rudimentary technologies is a bit like asking a young Moore to speculate about what people might do with billions of transistors in their pockets.

"We are basically back in 1969," Palacios says. The microprocessor was not yet invented. Intel had not been founded yet. The personal computer was not yet here. Nobody had heard of the internet. That's where we are today, with all the opportunities technology is going to give us. +

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(16) http://www.yole.fr/Silicon_Photonics_Market_Update_2021.aspx
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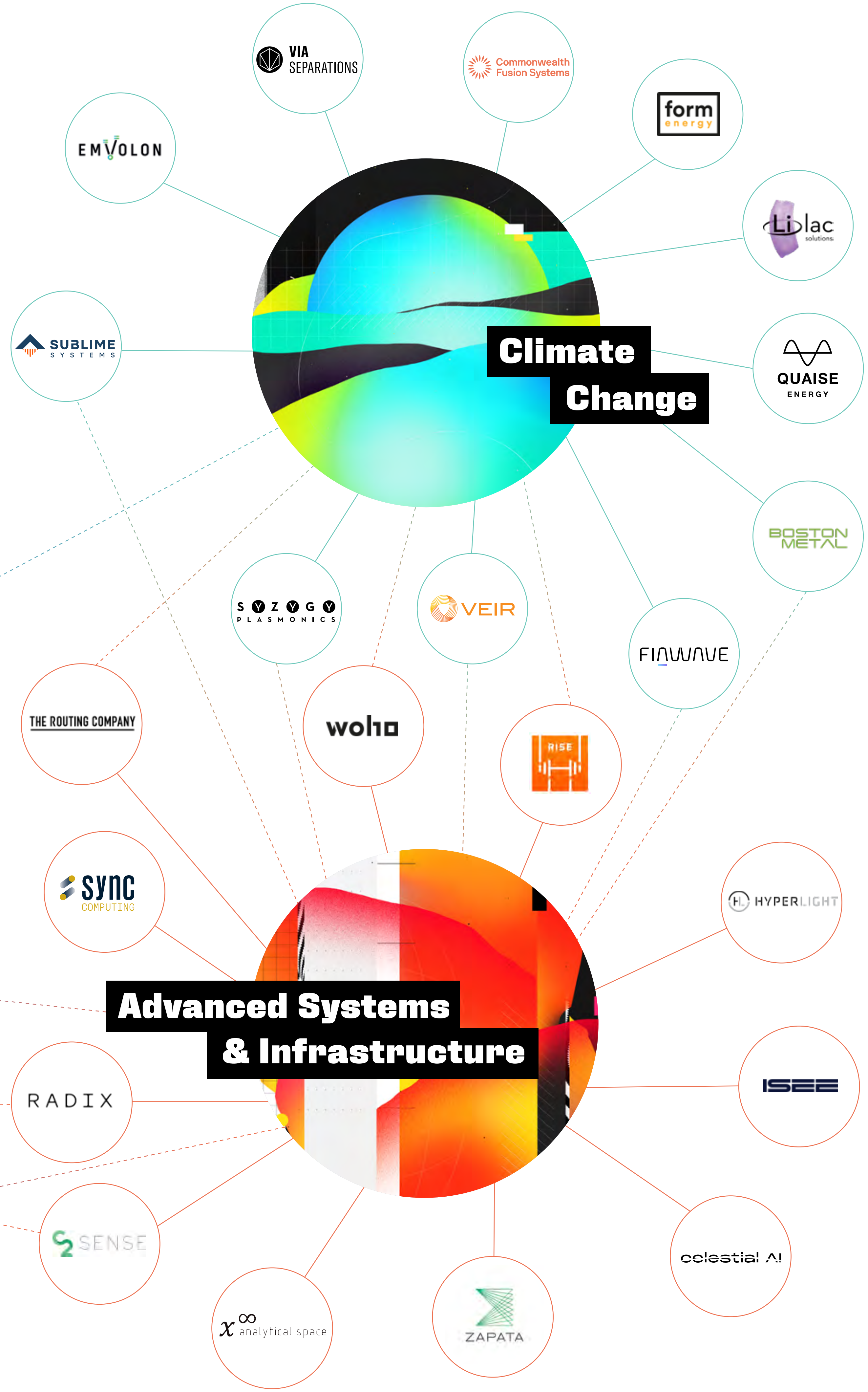
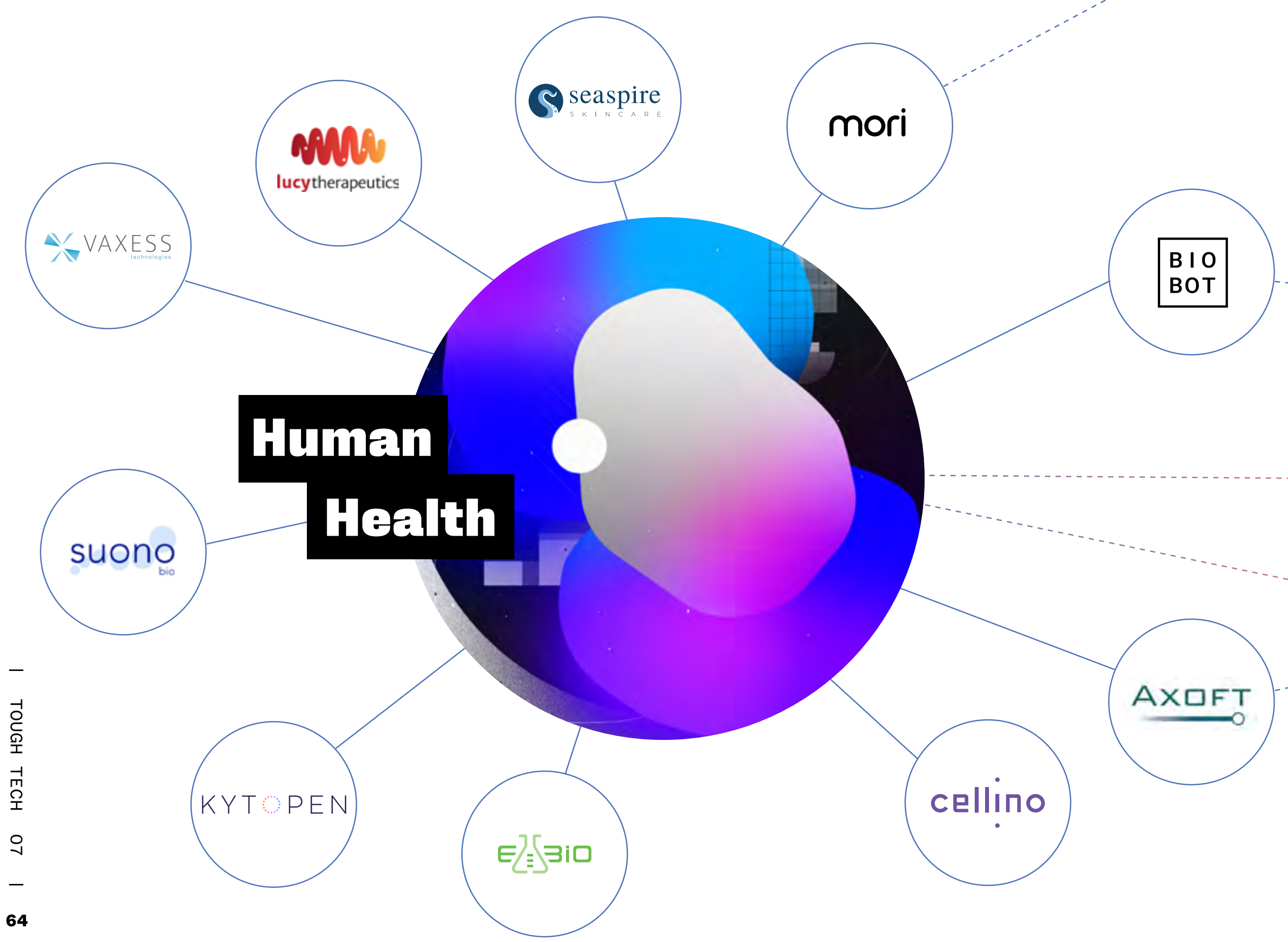
The Portfolio Companies

The Engine invests in founders solving the world's biggest problems through the convergence of breakthrough science, engineering, and leadership.

We've seen our investments coalesce into three areas of impact: those companies whose core technology will help solve climate change; those that will create new human health solutions; and those that will usher in a new era of advanced systems.





THE FOUNDERS

The Routing Company

Founders	|1| Menno van der Zee |2| Alex Wallar |3| James Cox |4| Bradford Church, Daniela Rus , Javier Alonso-Mora
Background	MIT, Uber, Canoo
Industry	Transportation, Artificial Intelligence, Machine Learning

Public transportation has a paradoxical effect on the communities it serves. While it is intended as an affordable transit option, communities with vibrant public transportation hubs may see higher housing costs, driving those who rely on public transit as their central mode of transportation further away from the transit options they need. And though it is true that public transportation is still available outside urban centers, trip time (and in many cases wait time) inevitably increases the farther from the city one catches a ride. This inefficiency drives the use of expensive ride sharing services, the mass adoption of which can contribute to more traffic congestion and more time on the road for us all.

The Routing Company, a startup born from work in MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL), is commercializing a software solution to public transit's limited reach and inefficiency. Its proprietary algorithms can optimize vehicle utilization at city scale, on demand, giving metropolitan areas the power to make their existing public transportation infrastructure more reliable and accessible than any other mobility option.

"Our technology effectively makes fleets responsive to fluctuating demand, regardless of peak usage windows, traffic patterns, or population density," notes James Cox, CEO. "We can optimize vehicle usage at scale and on demand to give cities the power to transform existing infrastructure and unlock the potential of ridesharing for reduced congestion, increased rider volume, and more reliable and accessible systems."

Cox works alongside CTO Alex Wallar, who co-founded The Routing Company after working as a PhD student in Daniela Rus's lab at CSAIL with postdoc Javier Alonso-Mora and others on algorithmic concepts that inspired the company's technology. The MIT team published a paper concluding that 3,000 typical four-passenger cars could serve 98 percent of taxi demand in New York City — versus the 14,000 cars on the street today — and, as an MIT News article on the study adds, the average wait time for these taxis would only be 2.7 minutes. The article goes on to highlight that 95%of taxi demand in New York City would be covered by 2,000 10-person vehicles. The optimization algorithms highlighted in the paper solved a challenge, according to Wallar, "that was much, much more difficult than the typical traveling salesman problem. It was holy grail type stuff."

Wallar notes that after the study was released, "there were no more interesting theoretical problems that would result in papers, but there were a ton of practical implementation challenges left to solve. It was after I realized this that I decided to leave academia and jump into the details — it was then I had the idea to start what would ultimately become The Routing Company."

Unbeknownst to Wallar, Menno van der Zee, an expert on mathematical optimization who was studying at one of Daniela Rus's satellite labs in Singapore, had tweaked the core algorithm released by Alonso-Mora and his team. Van der Zee sent Wallar a cold email noting that he had made the algorithm more efficient and that the two should meet. "I immediately booked a ticket to Singapore to talk to him [van der Zee]," Wallar recounts. "We nurtured that initial connection over many months and eventually became a finalist in the MIT 100K pitch competition, then were accepted into the associated summer accelerator program." Van der Zee is now The Routing Company's head of Global Business Development and a Co-Founder.

In spring 2019, as Wallar and van der Zee were discussing optimization strategies for the company's algorithms, the pair were introduced to James Cox, who had previously launched UberX in Sydney Australia and served as Uber's Global Head of Rider App Product Operations. Cox, now The Routing Company's CEO, recounts that it took him "two minutes" to decide to shift gears and work with Wallar and van der Zee: "the technology solved one of the hardest problems in transportation."

Cox has helped the startup make good on its promise to deliver on-demand transit "that moves with you," by refining the end-to-end business solution conceived by Wallar and van der Zee for metropolitan transit authorities. By providing these municipal services with an end-to-end software solution, The Routing Company expects to impact one-third of public transportation trips. As Cox notes, "we can give transit agencies the power to compete with ride sharing. We can help them more efficiently allocate the $71B the US spends in public transportation every year. We can give schedulers, planning managers, and other transit professionals a dynamic toolset to increase coverage equitably with the same budget — zero tradeoffs, just better service." This better service will have a profound effect on those riders who rely on public transit the most, bringing faster, easier, and less stressful transportation to an entire municipality's transportation network.

The Routing Company recently hired Bradford Church, the ex-lead for Uber Bus, as its Director of Product Management. Church, who led Uber Bus from concept to deployment, is an expert in mass transportation technology and operations and has deep experience launching mass transit products throughout the world. With his guidance, the startup plans to deploy its technologies in test markets in North America and Europe. It has already completed a test case with a mobility service in Europe, increasing serviceability from 83% to 97.5% with 50% fewer vehicles, boosting revenue and decreasing operating expenses.

The Routing Company has designed its product to be packaged in a standalone app known as Pingo that can be co-branded with local public transportation authorities. When downloaded, the app automatically connects with the local public transit fleet. All a rider has to do is hail a ride — the app does the rest, syncing with The Routing Company's algorithms, automatically (and invisibly) selecting the most efficient vehicle and route. Push button. Get transit.

Cox, Wallar, and van der Zee imagine a future in which anybody who needs affordable, reliable transportation will have it. It is a future in which public transportation is democratized in the most algorithmically perfect way. It is a future in which you can focus on work, play, family... and not worry about how you'll get there.+

Powering the future of public transit.

VEIR

Founders	**|1|** Adam Wallen **|2|** Tim Heidel, Steve Ashworth, Doug Stewart, Franco Moriconi
Background	MIT, Los Alamos National Laboratory, ARPA-E, Breakthrough Energy Ventures
Industry	Energy

Massive overhead high-voltage transmission lines weave across the United States, taking electricity from sites of power generation (power plants) to sites of power distribution (substations). Electricity is then routed through wires strung atop ubiquitous utility poles or underground, until it reaches its final destination. Unlike the wires connecting your home or business to the grid, transmission lines must handle thousands of kV and are strung between steel or wooden towers that can reach over 100 feet high.

This infrastructure is well established and supremely reliable, but what happens when existing lines run out of transmission capacity? (The U.S. is predicted to triple its transmission capacity needs by 2050 if aggressive, economy-wide clean energy goals are met.) The natural answer to such demand would be to simply build more transmission lines. But permitting the construction of thousands of 100-foot steel towers across the country is nearly impossible because of price, politics, and logistics. Nobody wants a tower in their backyard. And cities and towns have quite literally grown around existing rights-of-ways — there's no room.

VEIR, a startup born from technology conceived of by a National Laboratory researcher, plans to use superconducting tape bundled into a cable and surrounded by a novel cooling system to enable existing transmission infrastructure to transmit 5X more power at the same voltage, alleviating significant electric system pain points like congestion and renewable integration. No new towers required.

This transmission technology also unlocks the potential for renewable sources like solar and wind to power areas hundreds of miles from where the electricity is needed. An ancillary benefit to such efficient transmission is the elimination of fossil-fuel-powered "peaker" plants that kick in to supplement existing power when grid demand surges or "peaks."

VEIR is helmed by Adam Wallen (CEO) and Tim Heidel (CTO), who both previously worked for Bill Gates's Breakthrough Energy Ventures. Wallen is a serial entrepreneur with a background in ceramic sciences and engineering. Heidel earned his doctorate from MIT in electrical engineering and served both as Program Director for ARPA-E, where he managed over 75 ARPA-E funded research projects. He also helped lead the 2011 Future of the Electricity Grid study for the MIT Energy Initiative.

The startup's technology relies on the evaporative cooling power of liquid nitrogen to cool cables of high-temperature superconducting (HTS) tape. Unlike previous experiments with HTS transmission that relied on buried cables, complex mechanical refrigeration systems, VEIR's system is mostly passive, relying on the natural properties of nitrogen to transform from liquid to gas. And the active mechanical components of the system have proven reliable in the most demanding industrial applications like chemical refineries and steel mills.

"VEIR's technology enables increasing the amount of power transmitted in a given right-of-way by a factor of five. This will enable the transmission of more power at lower voltages in smaller rights-of-way, reducing the uncertainty, time, and cost of siting and permitting new transmission corridors." said VEIR CEO Adam Wallen. "The successful implementation of VEIR lines could form the backbone of an HVDC macrogrid, shifting massive amounts of renewable energy across the continent."

Electricity is the lifeblood of the modern world. Unfaltering access to it will only become more essential as industries push to decarbonize and we continue to electrify previously unelectrified sectors of the economy. The race to build the infrastructure to meet this coming demand is happening now. The International Energy Agency projects that global investments in the transmission system will exceed $1.8 trillion by 2035, $500 billion of which will be in the United States alone.

To fully realize a decarbonized electrified future, we need solutions that increase the capability of established rights-of-way by rethinking the arteries of the system itself — the transmission lines.+

Reinventing the architecture of electricity transmission to enable a fully decarbonized grid.

THE FOUNDERS

Emvolon

Founders	|1| Emmanuel Kasseris |2| Leslie Bromberg
Background	MIT Mechanical Engineering Department, MIT Plasma Fusion Energy Center, Chevron, ConocoPhilips
Industry	Advanced Manufacturing, Energy

Gas flaring is a wasteful practice in the oil and gas industry. Hydrocarbon-rich gas that is produced as a byproduct of oil production or oil and natural gas processing is burned on-site because there is no economically attractive way to transport it to market. The practice creates significant greenhouse gas emissions and other pollutants that negatively affect air quality in nearby communities.

Emmanuel Kasseris and Leslie Bromberg, the founders of Emvolon, see this gas as a stranded but extremely valuable resource. There is potential to turn gas that would be flared into useful in-demand liquid chemicals easily transported to market. The pair are pioneering a portable system built using inexpensive and ubiquitous diesel engines to execute such conversion at the site of the flares, eliminating transportation logistics and associated costs. Using mass-produced engines as mini chemical plants, Emvolon can achieve orders of magnitude cost reduction for small-scale chemical manufacturing.

The same device can be used to convert other stranded resources like biomass, which would otherwise rot in fields or forests, into a variety of useful chemicals. It can also be applied to distributed ammonia manufacturing, providing chemical energy storage for communities without reliable grid connections or renewable fertilizer.

Kasseris and Bromberg envision a world in which stranded resources are no longer wasted. One that efficiently and effectively harnesses every component of industrial processes to provide communities with necessary raw materials, without the need for massive refineries and chemical plants. Such a future would have a smaller carbon footprint while simultaneously enabling the on-demand and distributed production of chemicals.

"We're building on 100 years of engineering to deliver modular, customizable performance," Kasseris notes. "By leveraging economies of mass production, we will enable distributed chemical manufacturing when and where it is needed most."

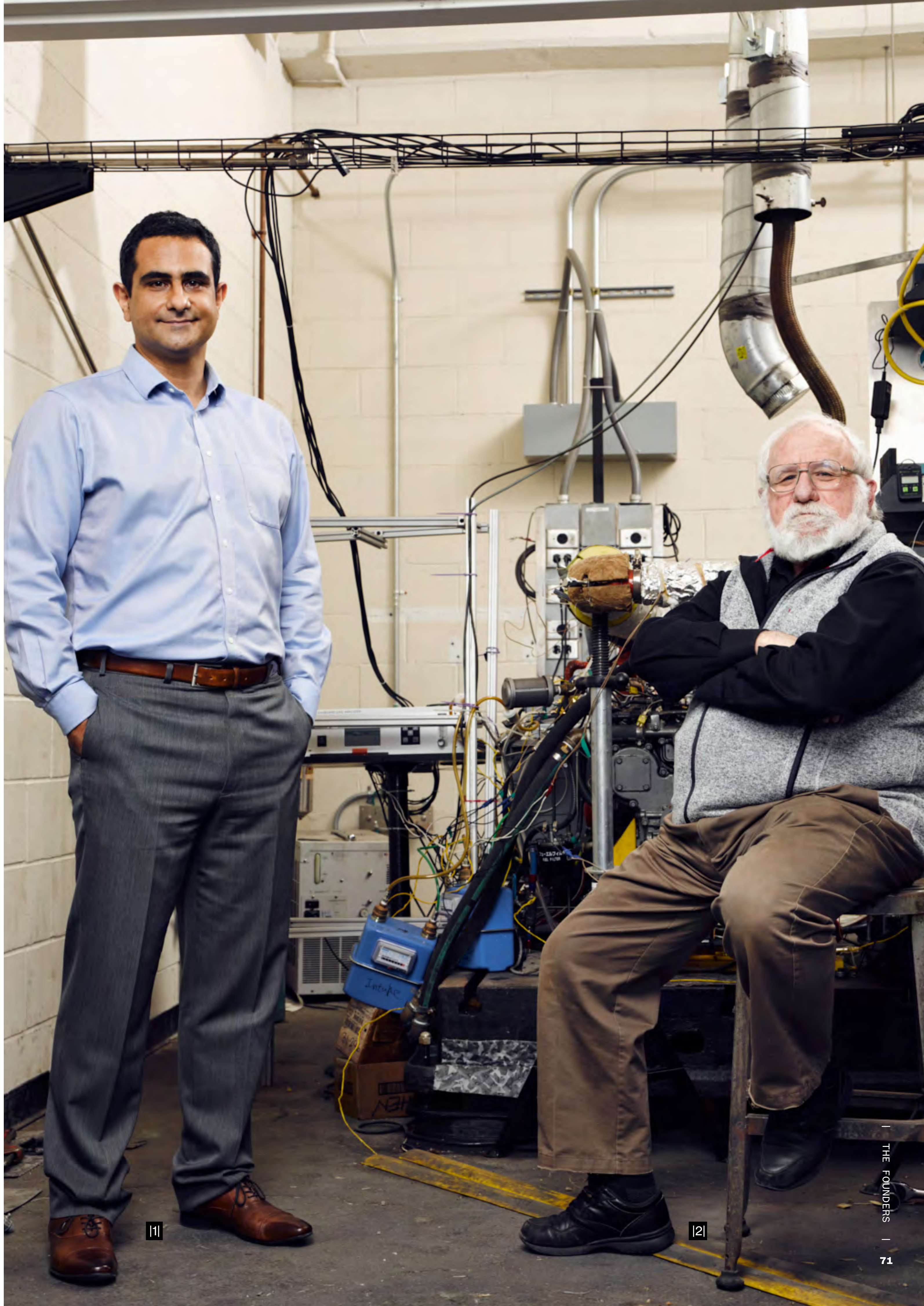
Emvolon grew out of Leslie Bromberg's work at MIT. Bromberg holds a PhD in Nuclear Engineering from MIT and has held various lead research roles in academia and the private sector for 40 years. A serial inventor, he also holds over 50 patents, many of which he has successfully commercialized.

Kasseris met Bromberg when he was working toward his own PhD at the MIT Mechanical Engineering department. But it wasn't until Kasseris had spent several years leading research, development, and commercialization efforts for energy technologies at Chevron and ConocoPhilips, as well as in academia, that he reconnected with Bromberg to formally pursue Emvolon.

During his career in the energy industry, Kasseris saw the problems and challenges with natural gas flaring first-hand. He also realized that if he were to make meaningful change in the industry, he'd have to do it from the outside, where he could experiment and innovate at a pace fast enough to make a difference.

"Our mission is simple," says Kasseris, "We will help global communities give new life to stranded resources that would otherwise be wasted. Whether they use these resources to produce power, fertilizers, or other chemicals, the impact is huge — less waste and the ability to make their own power, their own fertilizers, and their own chemicals without the need for massive infrastructure required for the conventional approaches." +

Converting wasted resources into valuable liquid chemicals through a low-cost, distributed platform.



|1| |2|

Sublime Systems

Founders	|1| Leah Ellis |2| Yet-Ming Chiang
Background	MIT
Industry	Advanced Materials

Humanity produces a staggering four billion tons of cement every year — it is the foundation upon which the modern world is built. And its environmental toll is equally as astonishing. For every kilogram of cement produced, one kilogram of CO_2 is released into the atmosphere. All that CO_2 accounts for eight percent of global emissions, or, to put that number into perspective, one gigaton more than the entire country of India. If we are to ever meaningfully combat climate change, we must decarbonize this industry.

Cement production creates CO_2 emissions in two major ways: generating the heat used to convert its raw materials, namely limestone, into clinker, the direct precursor to cement itself; and the chemical reaction that occurs when limestone is sintered, splitting the rock into lime and carbon dioxide gas.

Sublime Systems, founded by electrochemist Leah Ellis and serial entrepreneur Yet-Ming Chiang, is the first company with a potential pathway to decarbonizing both parts of the cement process, thereby producing cost-effective, zero-carbon cement. They call their product, aptly, electrochemical cement.

Sublime is applying proven industrial electrochemical concepts to create a platform that can scale to meet the world's demand for the building material. Aluminum, hydrogen, chlorine, magnesium, copper — all these commodities are produced using large-scale electrolytic processes. The techniques work. The company currently runs their process at a rate of kilograms per hour, and is working on scaling to tons per hour.

Sublime's platform converts limestone to lime at room temperature, making the CO_2 produced during the conversion process easier to capture and reducing overall energy consumption. In fact, Sublime's process can be completely powered by renewable electricity, in which case its operation is completely carbon-neutral.

Ellis, an electrochemist by training, spent the early part of her career working on lithium-ion batteries, optimizing them for EV use. Chiang's reputation precedes him in the battery and materials science worlds, having founded multiple companies including Desktop Metal, A123 Systems, Form Energy, and others. Ellis knew, if she had the chance, Chiang would be the person to work with on her next venture. When she received the prestigious Banting Postdoctoral Fellowship from the Government of Canada and an introduction to Chiang from Jeff Dahn, a lithium-ion battery pioneer, it was time to move to Cambridge, MA and get to work.

"I chose to solve cement's decarbonization challenge because of the impact any improvement to conventional processes would make," Ellis notes. "The cement industry and its emissions are equally massive — a one percent improvement in efficiency in this sector will have greater environmental impact than a one percent boost in battery efficiency. A small dent in a big problem creates a big impact."

Ellis and Chiang quickly realized that their platform would not just lead to small improvements in the efficiency of cement production, but rather a wholesale elimination of all emissions from the cement making process.

The pair remain realists, however; they know that changing an industry as mature and embedded as cement manufacturing takes time. "The challenge is humbling," Ellis is quick to point out. "But the opportunity is enormous." As Sublime's process matures, its superior product, zero emissions, and low production costs will make such change easy. +

Producing cost-effective, zero-carbon cement using renewable electricity.

THE FOUNDERS

Axoft

Founders	|**1**| Jia Liu |**2**| Paul Le Floch |**3**| Tianyang Ye
Background	Harvard University
Industry	Advanced Materials, Advanced Systems & Infrastructure, Biotech & Life Sciences

The merging of the brain and machine may sound like something from science fiction, but it is very real and happening today to help treat neurodegenerative conditions like Parkinson's disease. Such interfaces rely on ultra-thin wires implanted directly into brain tissue to selectively communicate with neurons. Yet, no matter how thin those wires are, they are still wires — and just like the wires in any electronic device, they are stiff and decidedly unlike the brain tissue in which they are embedded. These rigid materials can hurt the local brain region and pose significant challenges to avoid scarring and infection.

Axoft, a startup that grew out of research in the lab of Jia Liu at Harvard University, has created an entirely new class of brain implants that are >10,000x softer than plastics and >1,000,000x softer than silicon used in current brain implants. These new soft electronic materials are fabricated at the nanoscale and have similar mechanical and physicochemical properties to brain tissue itself. Liu spent his doctoral work devoted to developing methods of designing and fabricating ultra-flexible plastic mesh electronics to mimic the mechanical and structural properties of the neural network.

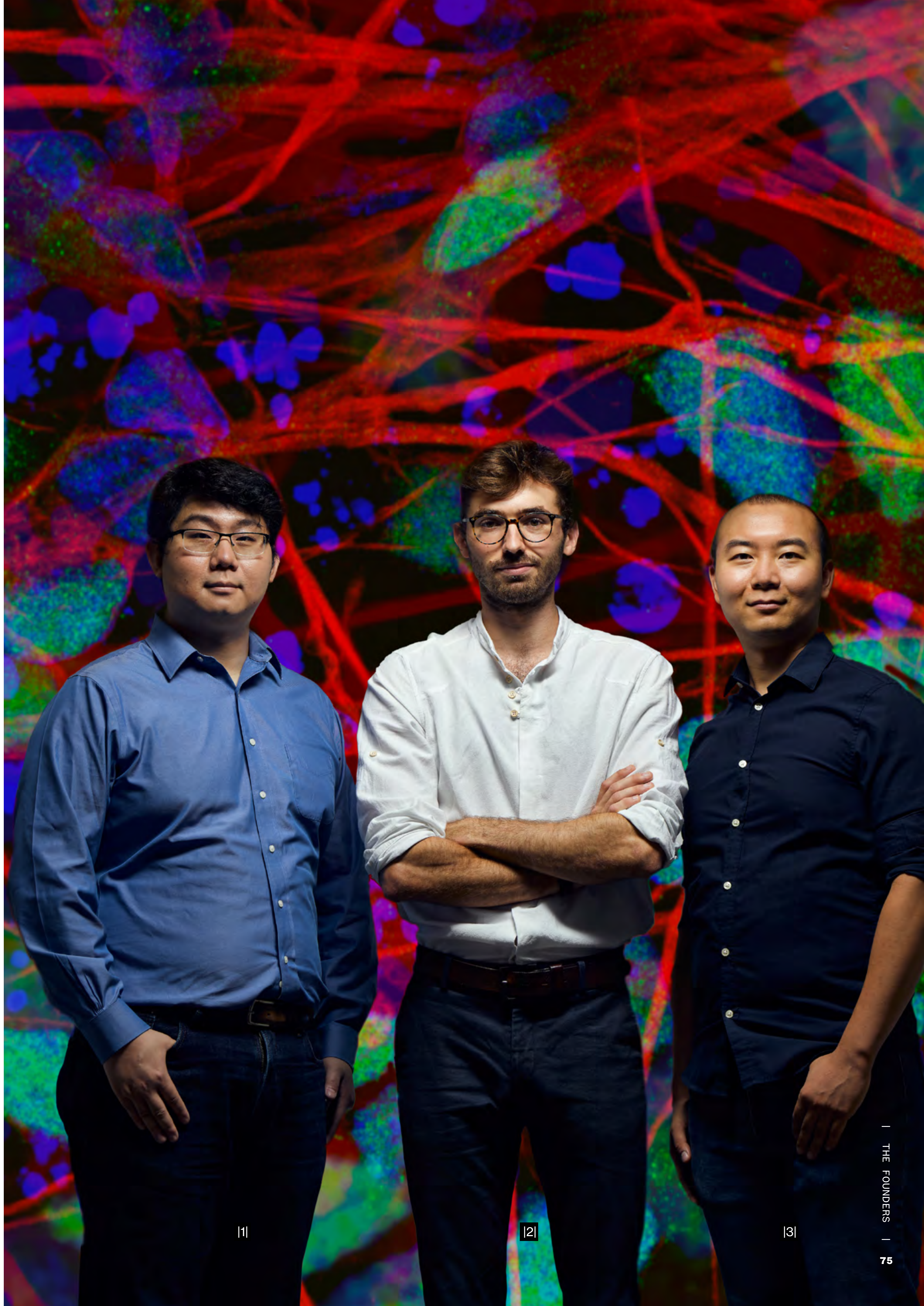
Paul Le Floch, Axoft's CEO, was Liu's first graduate student. And it was his work in Liu's lab that eventually led to the breakthroughs from which Axoft's core technology was created. His research helped make Axoft's brain implants not only soft, but also scalable, capable of integrating many sensors into one implant with the same mechanical properties as the brain. He imagines a future in which at least one million sensors could be integrated into a brain-machine interface, helping the blind with high-resolution artificial eyesight.

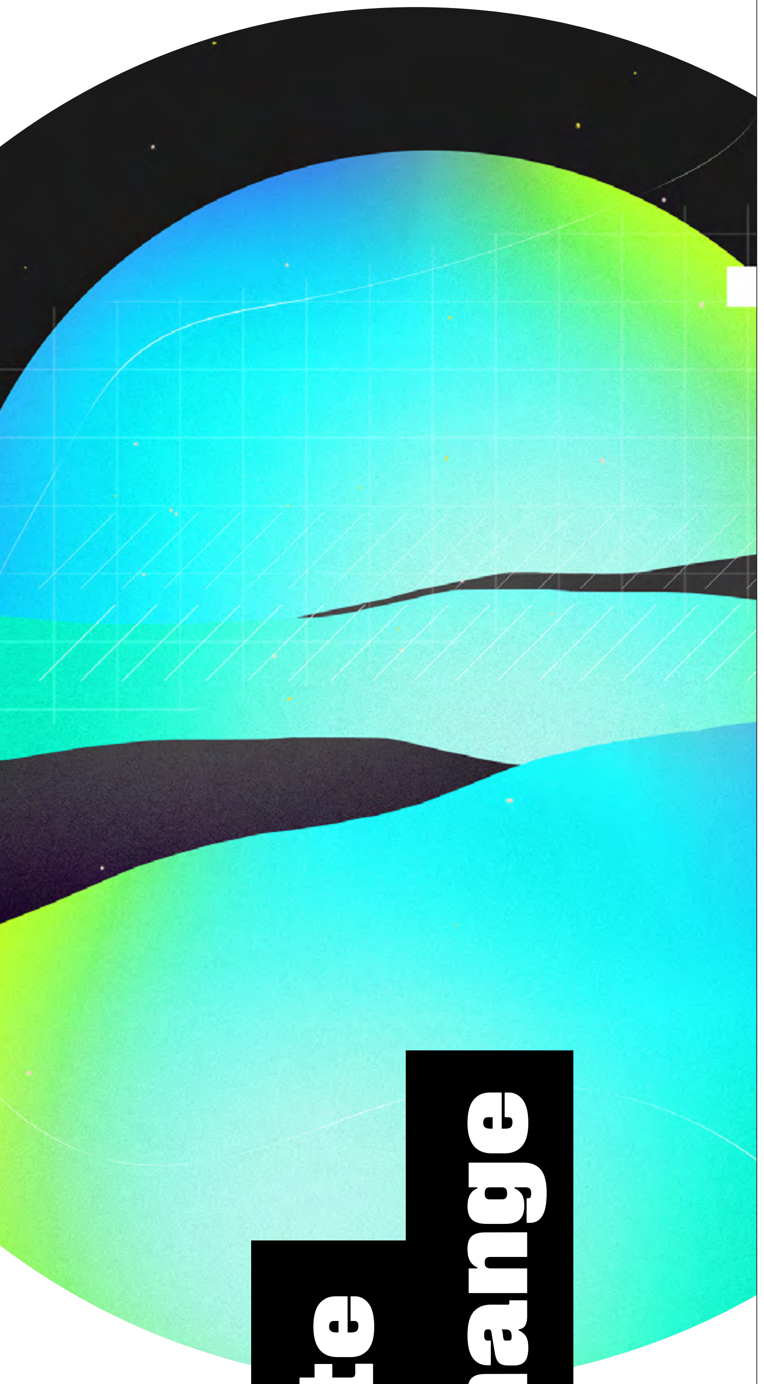
Tianyang Ye, another of Axoft's founders, also pursued his doctorate at Harvard, specializing in bioelectronics, a field at the intersection of nanotechnology and bio-engineering. His work has helped the team perfect their sensors' reactivity to the electrical signals emitted from our cells. Any future brain-machine interface must be able to detect and relay the nervous system's natural electrical impulses — impulses that are at once profoundly subtle and profoundly significant.

The team uses the analogy of 5G communications to describe the potential of its innovation — they are building the foundational infrastructure upon which future human brain-machine interfaces will be built. With its scalable and gliosis-free implants (implants that do not harm the central nervous system), its system can reside in the body for the long term. Le Floch, Ye, and Liu predict a future in which neurotechnologies will be regarded as standard as a pacemaker, an artificial joint, or a cochlear implant.

As the team works to clear a regulatory pathway with the FDA, it is doubling the number of electrodes its platform can accommodate — and therefore the number of neurons such a platform can stimulate — every 12 months. Such rapid progress, similar to the scaling of transistors in computing, means that hundreds of thousands of sensors are possible in just a few years (existing technologies cap out at only a small fraction of that amount). With those sensors comes the possibility of a new era in health and life, one in which machines, ironically, help us amplify what it means to be human. +

Building implantable electronics as soft as the brain to amplify brain-machine communication.





Climate Change

Boston Metal

The Problem

Manufacturing steel produces approximately 8% of global CO2 emissions. Today, the steel industry is the largest industrial source of CO2 emissions because of a reliance on coal.

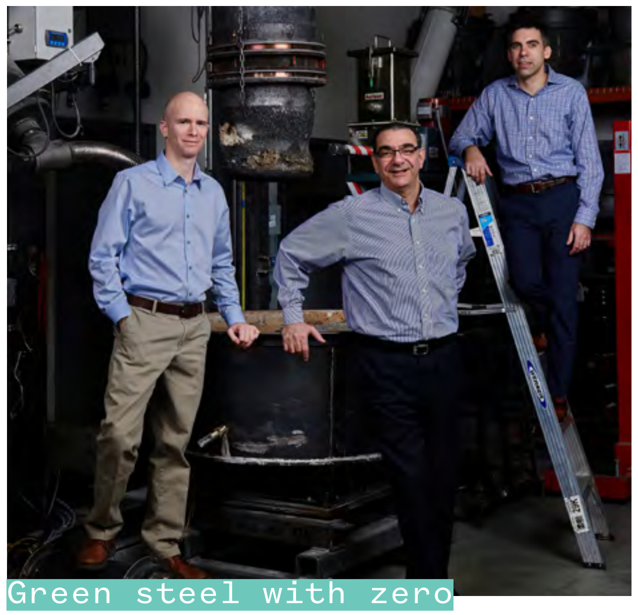
The Breakthrough

Boston Metal has invented a coal-free, emissions-free, modular method of industrial steel and ferroalloy production using electricity. It's called molten oxide electrolysis (MOE) and combines transformative materials engineering and novel systems engineering with elements from industrial aluminum production, traditional blast furnaces, and arc furnaces.

The technique produces steel more efficiently, at lower costs than traditional methods, and with zero greenhouse gas emissions.

The Impact

Boston Metal removes coal from the steelmaking process, driving CO2 emissions to zero, while also providing substantial OPEX and CAPEX savings.

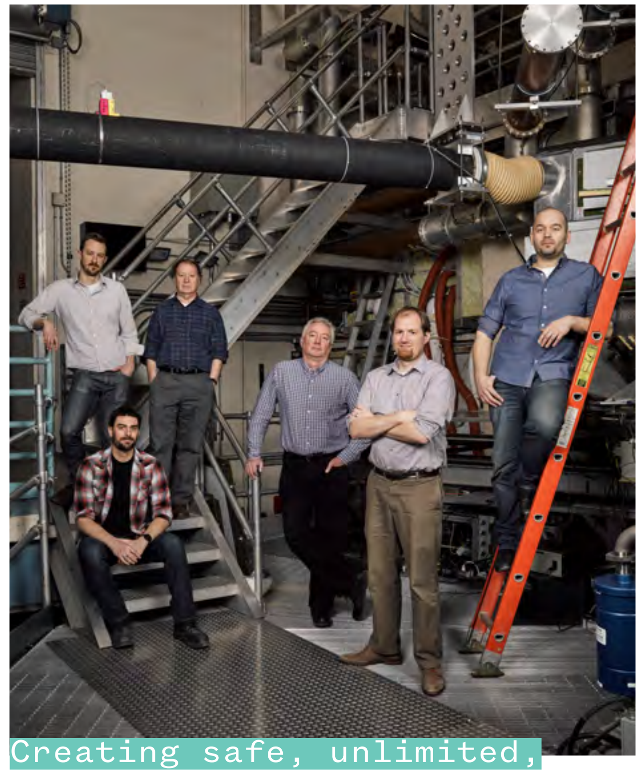


Green steel with zero greenhouse gas emissions.

Founders & Leadership
Tadeu Carneiro, Rich Bradshaw, Adam Rauwerdink, Donald Sadoway, Antoine Allanore, Jim Yurko, Bob Hyers

Background
MIT Department of Materials Science and Engineering

Industry
Advanced Manufacturing, Energy



Creating safe, unlimited, carbon-free fusion power for the grid in 10 to 15 years.

Commonwealth Fusion Systems

The Problem

Energy production is responsible for 25% of all GHG emissions.

The Breakthrough

Commonwealth Fusion Systems aims to provide a new path to fusion power by combining proven fusion physics with revolutionary magnet technology to deploy the first working, economically feasible fusion reactors to the world. The team will develop high-field magnets based on a new class of high-temperature superconductor materials that allow fusion reactors to be 10 times smaller, economically feasible, and operational in the next 10 to 15 years.

The Impact

Fusion energy is the holy grail of clean energy: limitless, no greenhouse gases, baseload, concentrated, no meltdown, and no proliferation. If fusion is successful, the world's energy systems will be transformed.

Founders & Leadership
Bob Mumgaard, Brandon Sorbom, Dan Brunner, Dennis Whyte, Martin Greenwald, Zach Hartwig

Background
MIT Plasma Science and Fusion Center

Industry
Energy, Advanced Materials

Form Energy

The Problem

The world needs ubiquitous renewable energy to successfully combat climate change. That energy needs to be stored and deployed on demand, but utility-scale renewable energy storage can only deliver power for up to four hours.

The Breakthrough

Form Energy has created a large-scale, modular and scalable, multi-day energy storage system built with novel metal-air chemistry. Using low-cost, globally abundant materials, Form's systems can be located in any market and scaled to match existing energy generation infrastructure. They have the capability to reshape the entire electric system, making renewable energy available year-round and extending transmission capacity without building new wires.

The Impact

A 100% renewable grid will eliminate 10Gt of CO2 emissions per year — or approximately 25% of all CO2 emissions worldwide.

Building multi-day energy storage systems that will enable a 100% renewable grid.

Founders
Mateo Jaramillo, Ted Wiley, William Woodford, Yet-Ming Chiang, Marco Ferrara

Background
MIT Department of Material Science and Engineering, 24M Technologies, A123, Tesla Energy

Industry
Energy, Advanced Materials

Lithium extraction with a 99% smaller footprint, 90% less water usage, and 80% fewer GHG emissions.

Lilac Solutions

The Problem

The world currently cannot meet the predicted 30X increase in demand for lithium to electrify the transportation sector.

The Breakthrough

Lilac Solutions is commercializing a new ion exchange technology for lithium extraction from brine resources that is significantly faster, cheaper, and more scalable than existing technology, enabling the massive increase in lithium supply needed for electric vehicles.
Lilac has successfully demonstrated the technology at large scale, and with dozens of brine resources from around the world.

The Impact

By eliminating evaporation ponds, Lilac's platform protects freshwater resources for the communities surrounding lithium brine reservoirs, reduces GHG emissions by 80%, and will help accelerate the transition to decarbonized transportation by providing a plentiful and affordable source of lithium to the producers of next-generation batteries.

Founders
Dave Snydacker, Nick Goldberg, Tom Wilson

Background
Northwestern University

Industry
Advanced Materials

Quaise

The Problem

The world cannot transition away from fossil fuels with current technologies. Geothermal is the largest source of power-dense clean energy on Earth, but there is limited access today.

The Breakthrough

Quaise is leveraging patented millimeter wave energy drilling systems to drill at depths (10-20km) accessing heat at the supercritical point for water. This enables geothermal to be a clean energy source anywhere on the planet, at a power density on par with fossil fuels. Deployment at scale builds on the capabilities of the oil and gas industry.

The Impact

Supercritical geothermal energy is one of the few new energy sources that can scale to meet the magnitude of the current climate crisis. Quaise's technology is able to meet the global electricity demand without sacrificing the Earth's carbon budget (a crucial component of the clean energy transition).

Developing millimeter wave drilling systems to unlock supercritical geothermal energy everywhere in the world.

Founders & Leadership
Carlos Araque, Matthew Houde, Henry Phan, Franck Monmont, Paul Woskov

Background
MIT

Industry
Energy, Advanced Materials, Advanced Engineering

Producing chemicals using light to reduce 1Gt of CO2 emissions by 2040.

Syzygy Plasmonics

The Problem

Making the chemicals that power our world emits massive amounts of CO2.

The Breakthrough

By replacing the heat in thermal catalysis with LED light powered by renewable electricity, Syzygy can perform reactions that produce materials and components of plastics, fuels, fertilizers, and other chemicals with far fewer greenhouse gas emissions.
At the heart of the reactor is a novel photocatalyst with 10,000x greater efficiency than the competition.

The Impact

Syzygy's technology platform allows for the production of chemicals on-site, in a modular, scalable, and cost-effective way, with reduced GHG emissions. The company will revolutionize the entire chemical manufacturing industry, opening new markets by avoiding the need to rely on costly or inefficient transportation chains.

Founders
Trevor Best, Suman Khatiwada, Naomi Halas, Peter Nordlander

Background
Rice University, Baker Hughes

Industry
Advanced Manufacturing

Via Separations

The Problem

Industrial thermal separations account for 12% of all U.S. energy consumption, or roughly the same amount of all the gasoline used for transportation in the United States.

The Breakthrough

Separation processes are the building blocks for materials, chemicals, and consumer goods — they are core to the industrial ecosystem. Currently, most separations are done with thermal processes such as evaporation and distillation, which are very energy-intensive. Via Separations is commercializing novel membrane materials and manufacturing processes to replace evaporation and distillation with filtration.

The Impact

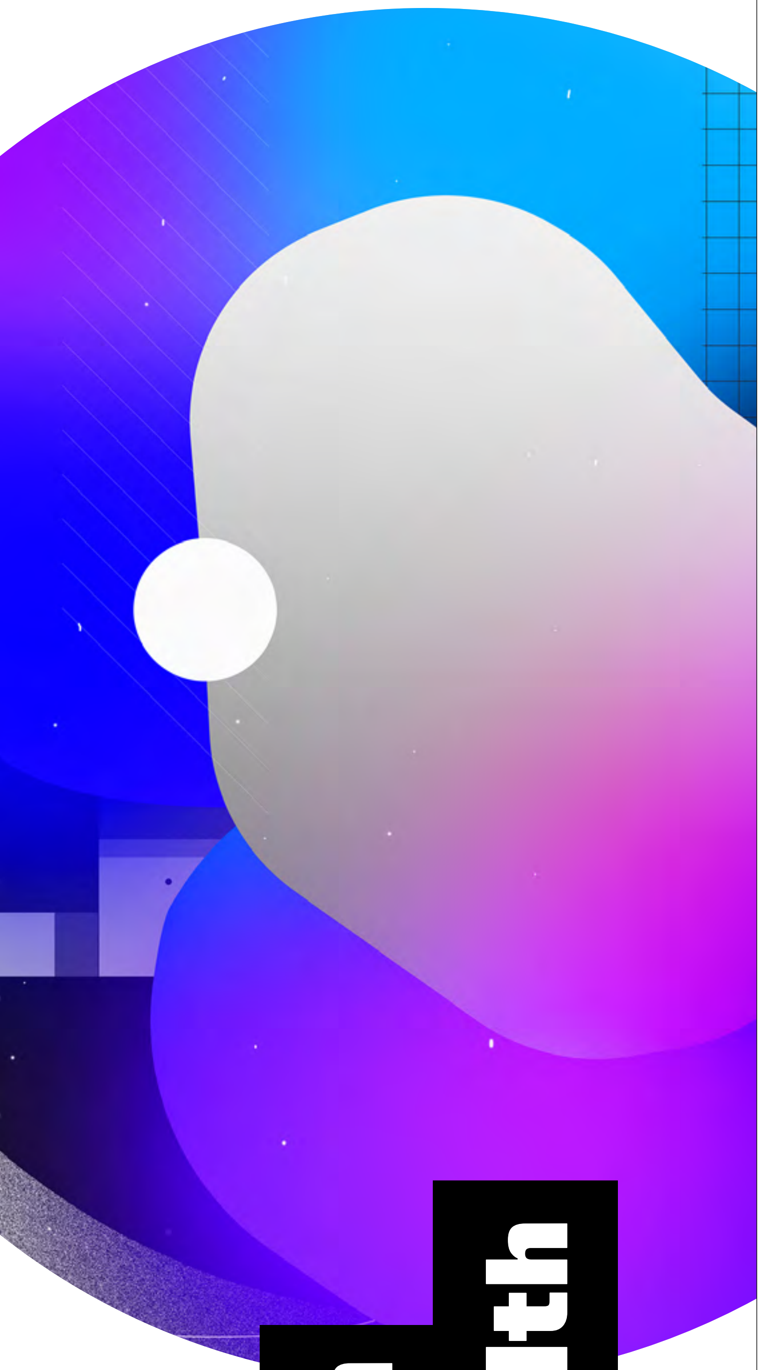
Via's technology has the potential to replace thermal separation processes, saving the energy equivalent used by the entire gasoline industry every year in the United States.

Decarbonizing every industrial process.

Founders & Leadership
Shreya Dave, Brent Keller, Jeff Grossman

Background
MIT Department of Materials Science and Engineering

Industry
Energy, Advanced Materials, Advanced Manufacturing



Human Health

Proactively identifying public health problems through sewage analysis.

Biobot Analytics

The Problem
Many public health problems are identified only after they have spread too far.

The Breakthrough
Biobot Analytics is a wastewater epidemiology company that is transforming wastewater infrastructure into real-time public health observatories. Its wastewater monitoring technology analyzes urine and stool samples to create health information that is independent from hospital reporting systems, free from societal biases affecting who can and can't seek care and, most importantly, is rapidly adaptable to new and emerging public health threats.

The Impact
Biobot's proprietary predictive models will provide insights for public health officials, citizens, and private sector partners to make more informed decisions to save lives and improve health through better resource allocation, interventional design, and more.

Founders
Mariana Matus, Newsha Ghaeli

Background
MIT

Industry
Biotech & Life Sciences, AI & ML, Data Science

Cellino

The Problem
Diseases like diabetes, heart disease, and Parkinson's claim nearly 750,000 lives per year in the United States alone.

The Breakthrough
Cellino is building a platform that enables the precise creation of cell and tissue therapies. Inspired by the scale and precision of semiconductor manufacturing, the Cellino Tissue Engineering Platform manufactures high-quality, impurity-free tissues at scale for new regenerative medicines.

The Impact
Cellino's approach for high-throughput, computer-guided engineering of human stem cells will create new tissues as regenerative medicines for patients. These tissues are poised to offer transformative benefits to patients and address significant unmet needs.

Automating personalized medicine to cure our toughest diseases.

Founders & Leadership
Nabiha Saklayen, Matthias Wagner, Marinna Madrid

Background
Harvard Physics Department, Harvard School of Engineering and Applied Sciences (SEAS), Harvard Medical School

Industry
Biotech & Life Sciences, Advanced Manufacturing, AI & ML

Developing affordable, simple, and scalable disease detection tools for everyone in the world.

E25Bio

The Problem
Current testing and detection platforms for infectious diseases are expensive, time-consuming, centrally-managed, and highly inefficient. This often results in delayed results and spread of the disease due to the lack of quick diagnostics.

The Breakthrough
E25Bio has developed rapid antigen tests for detection of infectious diseases such as COVID-19, Dengue, Zika, and others. These tests produce results in about 10-15 minutes without the need for any expensive equipment. As of June 2021, E25Bio has obtained regulatory approval in the EU and is distributing its COVID-19 tests in partnership with Perkin Elmer. They are also selling their Dengue test in Colombia.

The Impact
E25Bio believes in the decentralization and democratization of testing; every person should have access to diagnostic testing. E25Bio's rapid tests give people actionable information in minutes, not days, thus empowering them to take control of their health faster than ever before.

Founders & Leadership
Prashant Chouta, Bobby Brooke Herrera

Background
MIT Institute for Medical Engineering & Science, MIT Tata Center

Industry
Biotech & Life Sciences

Kytopen

The Problem

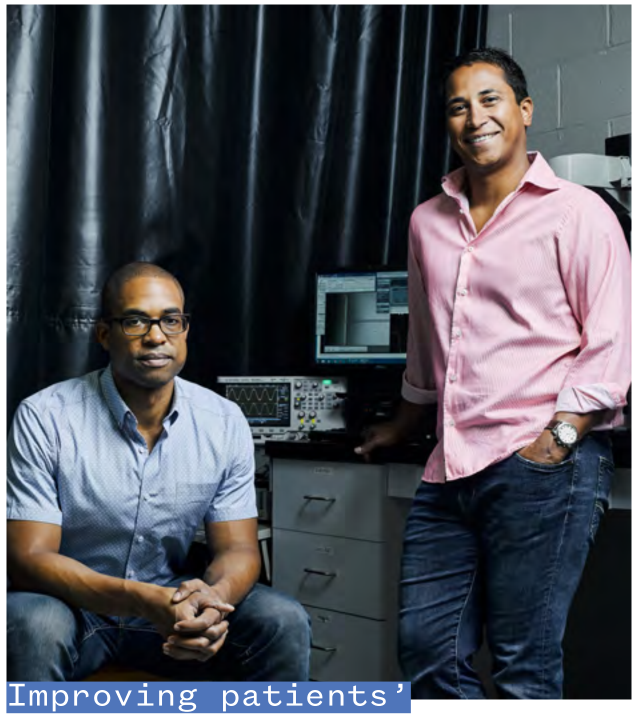
Engineered cells have the potential to save lives and cure some of our toughest diseases, but manufacturing them is currently a slow, laborious, and expensive process.

The Breakthrough

Kytopen has invented a new method of introducing genetic material into cells using continuous processing and electro-mechanical energy. This approach results in highly functional and healthy engineered cells in a fraction of the time and at a higher volume than other methods.

The Impact

With Kytopen's platform, more people will have access to life-saving engineered cell therapies. Its platform will accelerate time to clinic (an average of six months of time savings), reduce manufacturing timelines (from roughly a month to just days), and reduce the overall cost of developing therapies.



Improving patients' lives through automated cell engineering.

Founders & Leadership
Paulo Garcia, Cullen Buie

Background
MIT Department of Mechanical Engineering

Industry
Biotech & Life Sciences, Advanced Manufacturing

Using a unique mitochondrial-based approach to discover new ways to treat diseases of the brain.

Lucy Therapeutics

The Problem

Treatments for our most insidious neurodegenerative diseases remain elusive, even after decades of research.

The Breakthrough

Lucy Therapeutics is pursuing more effective medicines for neurological diseases such as Rett Syndrome, Parkinson's, and Alzheimer's by targeting pathways that modulate mitochondrial bioenergetics. This approach targets the mitochondria as a central player for many pathways known to be involved in these diseases. The insights behind Lucy Therapeutics are also driving biomarker discovery to enable early, presymptomatic diagnosis of diseases.

The Impact

Imagine a world in which doctors can diagnose and treat patients before the tremors, dementia, or seizures from neurological diseases like Rett Syndrome, Alzheimer's, and Parkinson's take control. This is the world that Lucy Therapeutics is working to realize.

Founders & Leadership
Amy Ripka

Background
University of Wisconsin-Madison, The Scripps Research Institute

Industry
Biotech & Life Sciences

Mori

The Problem

About a third of the food produced globally is wasted, and our packaging for food is only adding to sustainability challenges.

The Breakthrough

Mori is pioneering a natural coating — a water-soluble powder designed to integrate seamlessly into existing harvesting, processing, and distribution workflows — that takes advantage of silk's innate preservative qualities to slow down the spoiling processes across whole and cut produce, protein, packaging, to name just a few cases.

The Impact

Mori will improve access to fresh food with less waste, increasing resiliency and sustainability in the global food supply chain. This will give more of the world access to safe and healthy food that will remain fresher for longer — without the need for single-use plastic packaging.

A natural coating that reduces food spoilage and packaging waste.

Founders & Leadership
Adam Behrens, Sezin Yigit, Benedetto Marelli, Livio Valenti, Fiorenzo Omenetto

Background
MIT Laboratory for Advanced Biopolymers, Tufts University SilkLab

Industry
Food & Agriculture, Advanced Materials

Sustainable, bio-inspired materials for sunscreens and cosmetics.

Seaspire Skincare

The Problem

More than 70% of suncare products contain chemical UV-filters that have been reported to disrupt the endocrine system. Such UV-filters can also adversely affect the health of coral reefs.

The Breakthrough

Seaspire discovered that cephalopod-derived Xanthochrome can function as an SPF booster, UV filter stabilizer, and antioxidant with activity that rivals vitamins C and E but with increased stability. Xanthochrome outperforms current active ingredients found in OTC skincare products in performance, safety, aesthetics, and function.

The Impact

Seaspire will expand the availability of natural ingredients that can be used to prevent skin damage and cancers caused by environmental pollutants such as sunlight, smog, blue light, and oxidation. Its natural ingredients will not adversely affect marine life or the environment.

Founders & Leadership
Camille Martin, Leila Deravi

Background
Northeastern University

Industry
Advanced Materials

THE FOUNDERS

Suono Bio

The Problem

Ulcerative colitis impacts almost one million patients in the United States alone. Poor treatment options lead to exorbitant medication spending in excess of $10B annually.

The Breakthrough

Suono's core technology leverages low-frequency ultrasound. The company's founding team demonstrated that through an ultrasound-induced phenomenon known as transient cavitation, drugs are gently "pushed" into the tissue, achieving ultra-rapid delivery of therapeutics.

The Impact

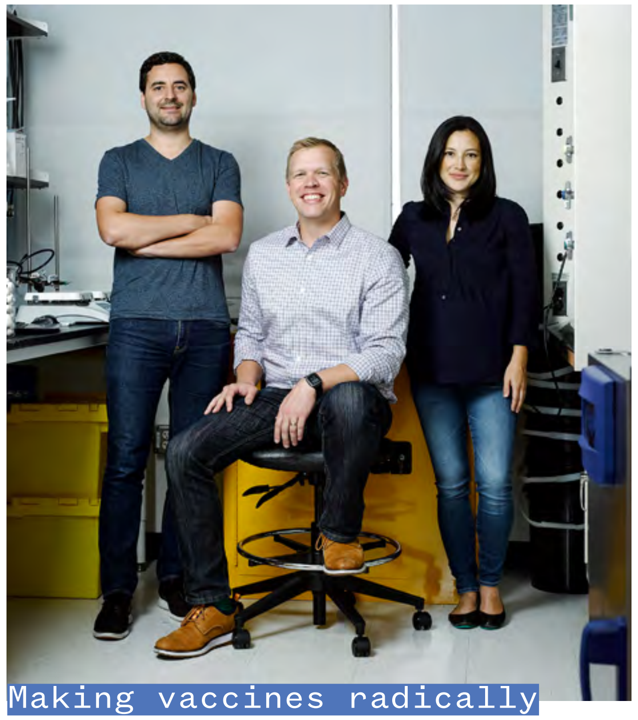
Suono Bio is pioneering a platform technology for local, ultra-rapid administration of therapeutics in the GI tract that can deliver 10X the drug in only one minute. Suono can also deliver nucleic acids (e.g., mRNA) that today can't be delivered to the GI tract.

Delivering drugs to the gastrointestinal tract more efficiently and effectively using a novel platform technology.

Founders & Leadership
Carl Schoellhammer, Robert Langer, Gio Traverso, Scott Kellogg

Background
MIT Department of Chemical Engineering

Industry
Biotech & Life Sciences



Making vaccines radically more effective and accessible via a shelf-stable patch.

Vaxess Technologies

The Problem

Often, vaccination does not provide a person with sufficient protection from disease furthermore, the vaccine is challenging to transport, prepare, and administer to people around the globe.

The Breakthrough

Vaxess is pioneering MIMIX, a product platform for increasing the effectiveness of vaccines inspired by the body's natural immune system. The platform enables vaccines based on proteins or mRNA, stabilizing the vaccines at room temperature. MIMIX is a smart release therapeutic patch that, after only a minute of wear time, can release treatment into the skin for months after initial application.

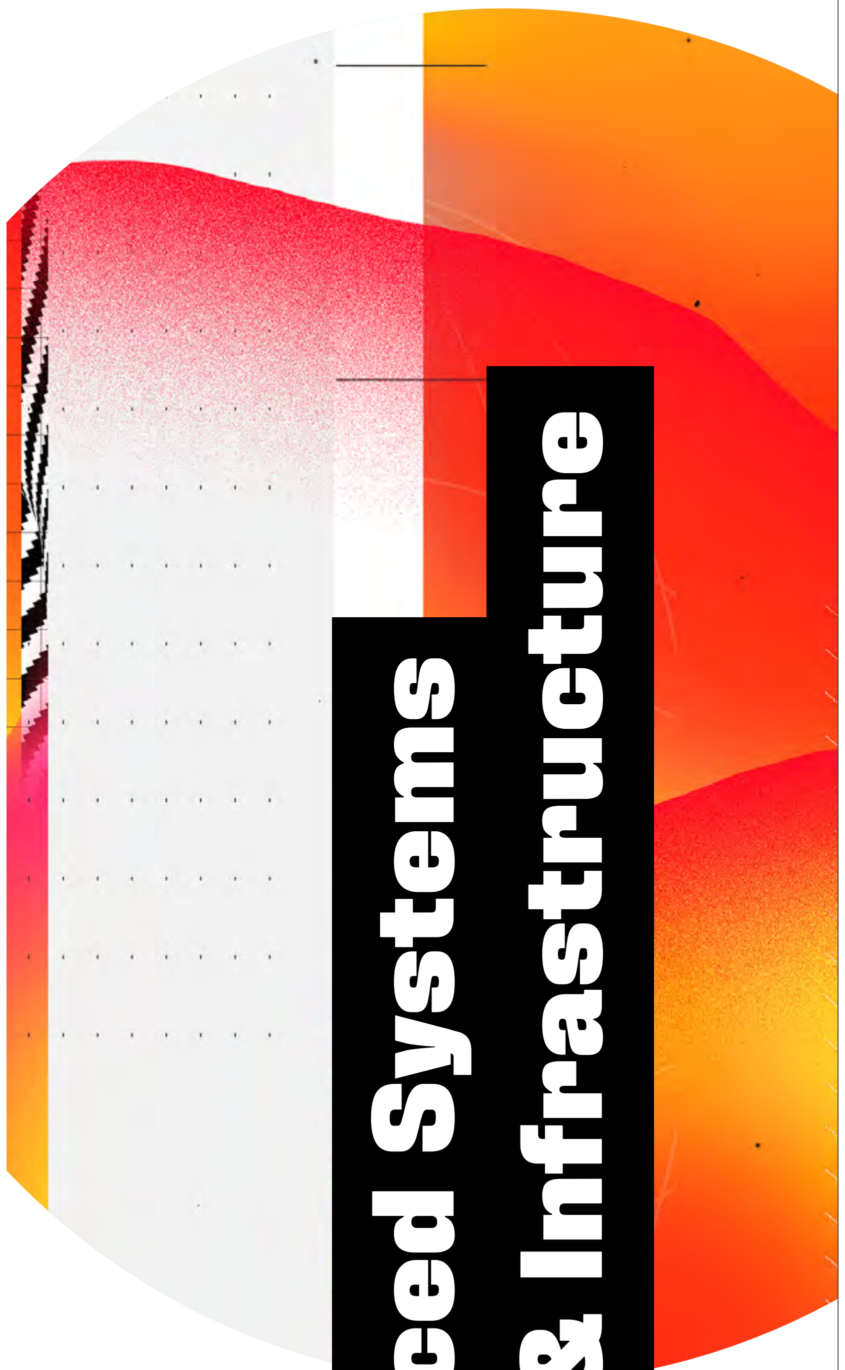
The Impact

Vaxess is transforming efficacy and access for vaccines. Its patch-based products are shelf-stable, easily administered, and have better efficacy than those administered traditionally.

Founders & Leadership
Michael Schrader, Kathryn Kosuda, Livio Valenti, David Kaplan, Fiorenzo Omenetto

Background
Harvard Business School, Tufts University SilkLab

Industry
Biotech & Life Sciences, Advanced Materials, Advanced Manufacturing



Advanced Systems & Infrastructure

Analytical Space

The Problem

Remote sensing satellites lack basic connectivity in orbit. We need real-time imagery from space to keep the planet safe and prosperous.

The Breakthrough

Analytical Space is building a network of in-orbit communication relay satellites that offers expanded connectivity for data transfer, without any change to existing hardware. This results in faster data downloading, more access to download windows, lower latency, and improved cost structures while being compatible with heritage satellites and new satellites alike.

The Impact

Analytical Space will liberate and deliver terabytes of untapped data gathered by thousands of satellites, helping industries from agriculture to defense operate with greater precision, efficiency, and insight.

Connecting space to Earth 24/7 to help us better understand and protect our world.

Founders & Leadership
Dan Nevius

Background
NASA, Planetary Resources, White House, HBS

Industry
Space, Internet of Things

Advanced sensing solutions for a healthier and safer world.

C2Sense

The Problem

Outdated sensing solutions and slow, costly, lab-based analyses limit rapid and widespread access to invisible chemical signatures. As a result, critical information on diseases, toxins, and product integrity have remained under-reported and inaccessible.

The Breakthrough

The unique combination of advanced molecular recognition, detection hardware, and AI-driven software is a fundamentally new way to interact with the world. The technology platforms designed by C2Sense make the detection of invisible compounds and the power of rapid diagnosis readily available and affordable.

The Impact

C2Sense technology has a wide range of applications, including sensing platforms to monitor air, food, and water quality, diagnostic tools to bring lab accuracy into the home, and counterfeit detection solutions for products across markets. These sensing solutions are designed to make the world a healthier and safer place.

Founders & Leadership
George Linscott, Tim Swager, Eric Keller, JT Mann

Background
MIT Department of Chemistry

Industry
Advanced Materials, Internet of Things

Celestial AI

The Problem

AI is driving unprecedented demand for computation just as the physics of digital semiconductors is failing to continue to support Moore's Law. Transistor scaling has reached its limits, and AI accelerator companies are struggling to keep pace with demands, particularly in edge applications that require greater power and cost-efficiency.

The Breakthrough

Celestial's breakthrough is its opto-electronic system-in-package that includes the photonic neural network integrated with a state-of-the-art AI accelerator chip.

The Impact

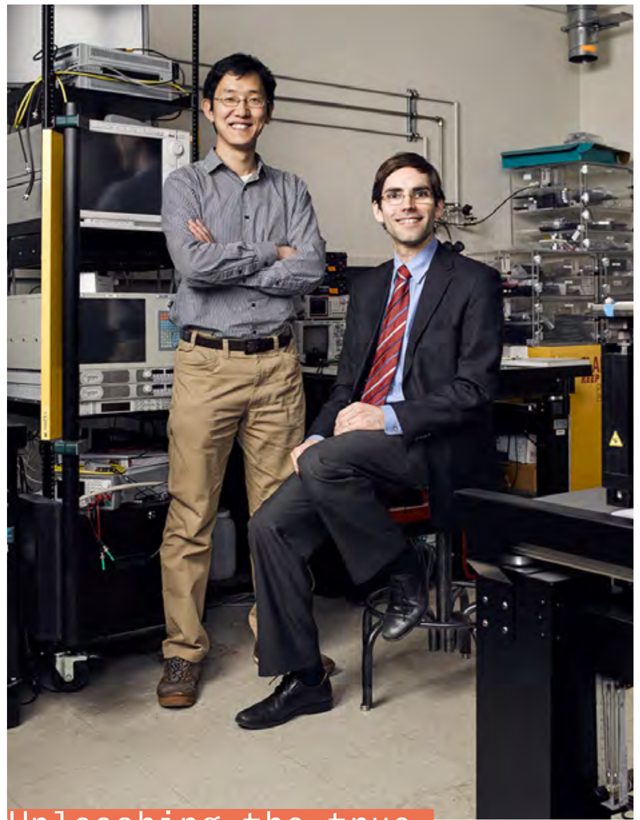
Celestial has developed a proprietary photonic neural network processor that uses photons (light) rather than electrons to handle data-parallel calculations that are many orders of magnitude faster and more power-efficient than in traditional semiconductors. This speed and efficiency will liberate the power of AI in every application, especially at the edge, where energy use is of paramount concern.

Harnessing photonics to lead the next wave of advancements in AI computation.

Founders & Leadership
David Lazovsky, Preet Virk, Michelle Tomasko

Background
Intermolecular, POET Technologies, NVIDIA, Google, Groq, MACOM, Transmeta, Applied Materials

Industry
Semiconductors, Artificial Intelligence, Machine Learning



Unleashing the true power of 5G.

Finwave

The Problem

The poor energy efficiency of silicon (Si) semiconductor chips is the most critical problem that prevents the wide adoption of 5G broadband services, as well as constraining the performance and efficiency of data centers, to cite only one example.

The Breakthrough

Overcoming the constraints of Si chips by developing a new generation of semiconductor devices and chips based on a revolutionary gallium nitride (GaN) technology. Using a novel three-dimensional structure, Cambridge Electronics' GaN chips promise significant performance improvements in both 5G radios and the power electronics in data centers and electric cars.

The Impact

Significant energy savings in diverse industrial sectors like 5G, data centers, renewable energy, manufacturing, automotive, and consumer electronics.

Founders & Leadership
Bin Lu, Tomás Palacios

Background
MIT Microsystems Technology Laboratories, MIT Department of Electrical Engineering and Computer Science

Industry
Semiconductors, Advanced Materials

HyperLight

The Problem

Data centers are quickly reaching limits of speed and energy consumption. Without significant innovation in material efficiency, the quantity of data and the transmission speed of that data will reach a ceiling.

The Breakthrough

HyperLight has invented unique processes and designs for fabricating integrated, chip-scale lithium niobate (LN) modulators with extremely low signal loss. These integrated optical circuits have the potential to reshape the world's relationship with optical data and enable novel functionalities from communication to spectroscop.

The Impact

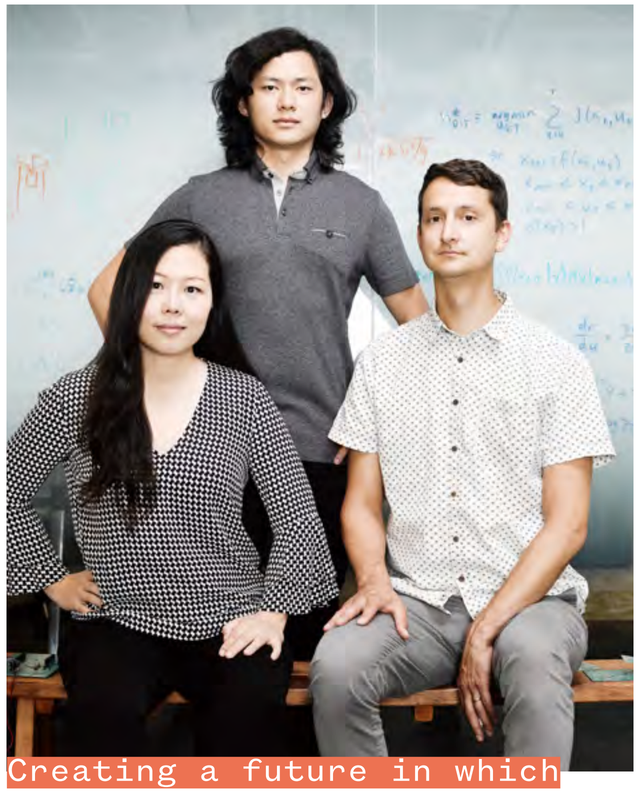
The information age relies on billions of devices converting signals between electricity and light waves. These integrated light circuits are the backbone of telecommunication, data centers, and even secure quantum communications. HyperLight's devices will force industries to rethink and reimagine their standards.

Redefining the possibilities of the world's communication infrastructure with ultra-high-speed, low-power circuits.

Founders & Leadership
Mian Zhang, Marko Loncar, Cheng Wang

Background
Laboratory for Nanoscale Optics at Harvard University

Industry
Semiconductors, Advanced Materials, Advanced Manufacturing



Creating a future in which autonomous machines can thrive alongside humans, seamlessly and safely in any environment.

ISEE

The Problem
Autonomous vehicles cannot fully predict unexpected behavior, resulting in increased risk and slow rollouts of new technologies.

The Breakthrough
ISEE's technology is built for complex environments with high uncertainty (shipping yards and congested highways) and can integrate into an existing logistics workflow without new infrastructure. Its AI understands human decision making and is designed to enhance performance and safety in the transportation and logistics markets.

The Impact
ISEE plans to first automate the shipping yard, reducing yard costs by 50% and increasing yard throughput by 30%. The same AI that will power yard trucks, can be used to transport freight across our highways — it will add value and increase safety throughout the logistics supply chain.

Founders & Leadership
Yibiao Zhao, Debbie Yu, Chris Baker

Background
MIT Computational & Cognitive Science Group

Industry
Deep Software & AI

Radix Labs

The Problem
Today's biology lab is inefficient and prone to human error. Its machines, the equipment tasked with unlocking some of life's most profound mysteries, can't talk to each other. Humans perform repetitive tasks by hand without precise documentation. Reproducibility of results by peers is difficult or impossible.

The Breakthrough
Radix has built a programming language that unites biologists and their lab machinery in one automated unit. This programming language is the heart of software that manages both human and machine tasks. It is the first time disparate lab machinery can communicate with one another under the control of one centralized platform.

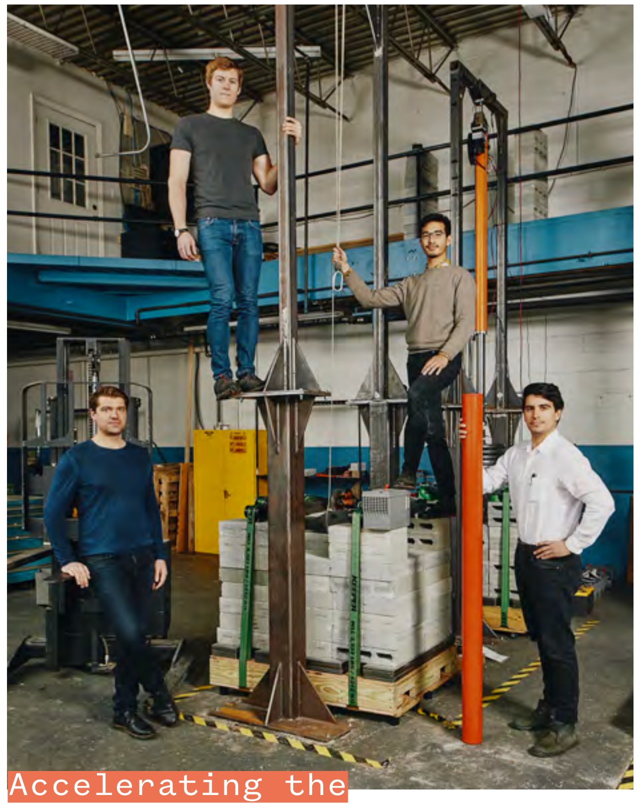
The Impact
With Radix, biologists will spend less time in the lab and more time focusing on experimental design and analysis. Its software requires no coding and is designed around an approachable user interface.

Making complex lab work radically simple by uniting scientists and lab machinery through software.

Founders & Leadership
Dhasharath Shrivathsa

Background
Olin College, MIT Media Lab

Industry
Robotics, Deep Software & AI, Internet of Things, Biotech & Life Sciences



Accelerating the electrification of heavy machinery with solid-state hydraulics.

RISE Robotics

The Problem
Heavy machinery consumes 14B gallons of diesel, resulting in 154M tons of CO_2 annually in the United States. Worldwide, 570M tons of CO_2 are emitted every year.

The Breakthrough
RISE Robotics has invented a replacement for hydraulic systems that will enable the next era of fully electrified heavy machinery, one that is simultaneously sustainable, robust, and precise. Their core technology is an electrically powered mechanical linear actuator with all the abilities of a hydraulic cylinder but vastly improved efficiency and control.

The Impact
RISE Robotics will make electrification of heavy equipment practical, driving progress toward heavy machinery becoming an oil-free, zero-emissions industry in the future.

Founders & Leadership
Arron Acosta, Blake Sessions, Toomas Sepp, Kyle Dell'Aquila

Background
MIT

Industry
Robotics

Sync Computing

The Problem
The $300B global cloud computing industry is massively inefficient and complex, contributing to tens of billions of dollars of wasted time and electricity a year.

The Breakthrough
Sync Computing's core technology uses a radically new circuit architecture for solving combinatorial optimization problems. It can quickly optimize complex cloud infrastructure for cost and time.

The Impact
By eliminating the guesswork, cloud applications such as big data analytics, machine learning, and scientific simulations can be instantly and optimally deployed to the cloud, saving companies billions of dollars.

Optimizing the resources at the heart of every cloud computation.

Founders & Leadership
Jeff Chou, Suraj Bramhavar

Background
MIT Lincoln Lab

Industry
Computing

Changing how we design and construct our world.

WoHo

The Problem

The housing industry is in crisis, with a scarcity of labor, higher prices, fragmented supply chains, and high demand.

The Breakthrough

WoHo is transforming the way spaces are conceived and created. The company integrates architectural design, engineering, and construction into a single, streamlined platform to quickly build resilient, sustainable, high-rise buildings.WoHo will build lean, modular factories that balance automation and handwork close to construction hubs, simplifying the logistics, lowering the costs, and reducing the environmental footprint of its buildings.

The Impact

WoHo expects to lower the costs of construction by more than 20%, shrink project delivery time by 50%, and reduce the ecological footprint of buildings by 70%, all while improving project predictability and construction quality.

Founders & Leadership
Israel Ruiz, Débora Mesa, Antón García-Abril

Background
Advanced Materials, Advanced Manufacturing

Industry
MIT, Ensamble Studio

Zapata Computing

The Problem

Classical computers lack the power to solve the most important problems in science and industry.

The Breakthrough

Zapata Computing writes algorithms that harness the power of quantum computing to help predict and simulate some of the universe's most complex interactions, such as the behavior of molecules at an atomic level. The company's 25 quantum scientists and engineers have produced over 495 peer-reviewed publications in the discipline.

The Impact

By creating algorithms that bridge advances in quantum computing hardware and commercial applications, Zapata has the potential to solve problems and accelerate discoveries in industries across pharma, logistics, aerospace & automotive, finance, materials, and much more.

Creating quantum software to solve our most complex problems.

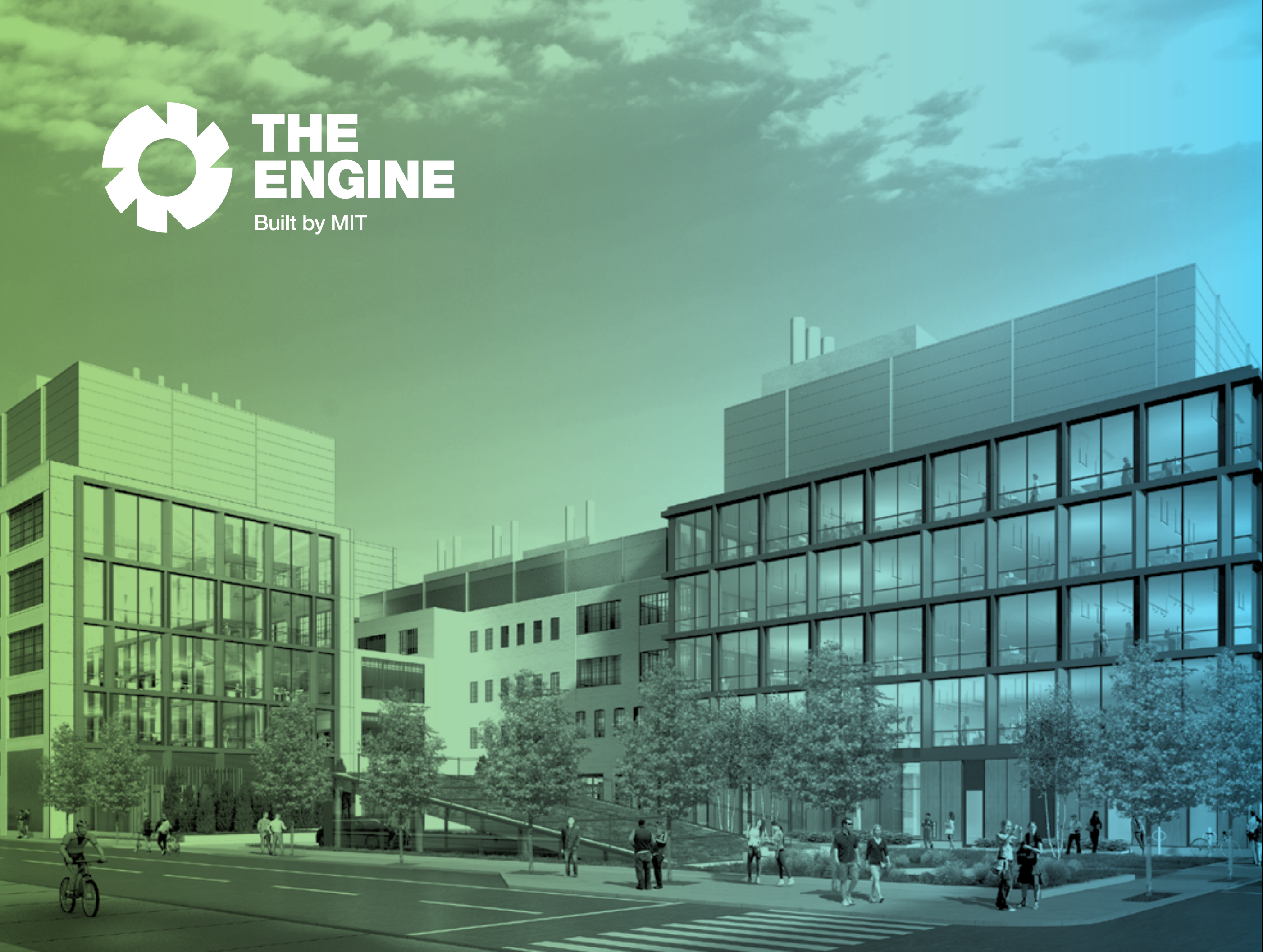
Founders & Leadership
Christopher Savoie, Alán Aspuru-Guzik, Jonathan Olson, Peter Johnson, Yudong Cao, Jhonathan Romero Fontalvo

Background
Harvard Department of Chemistry, University of Toronto Department of Chemistry

Industry
Quantum Computing

> "These teams implicitly embrace the responsibility we have to elevate one another, and we are truly proud to support and accelerate their missions."

ANN DEWITT
General Partner, The Engine



The Engine | *750 Main Street, Cambridge, MA 02139*

The Engine Expansion

Opening Fall 2022

155K Sq/ft of space for Tough Tech Companies

- BIOLOGY & CHEMISTRY LABS
- OPEN INDUSTRIAL SPACE
- ENGINEERING LABS & MACHINE SHOP
- 3D PRINTING, LASER CUTTER & PROTOTYPING LABS
- OPEN OFFICE SPACE & OFFICE SUITES
- EVENT SPACE & CONFERENCE ROOMS
- CAFE & COLLABORATIVE SPACES
- SECURE SPACE & WIFI

For more lab and office details, visit: bit.ly/engine_expansion

Tough Tech Summit® 2021
Build 10.27 — Invest 10.28

Explore the challenges and opportunities of bringing Tough Tech to market and how the ecosystem can work together to accelerate the commercial success of world-changing technologies.

Join founders, entrepreneurs, investors, policymakers, industry leaders, and others for two days of keynotes, panels, case studies, and networking.

Day 1

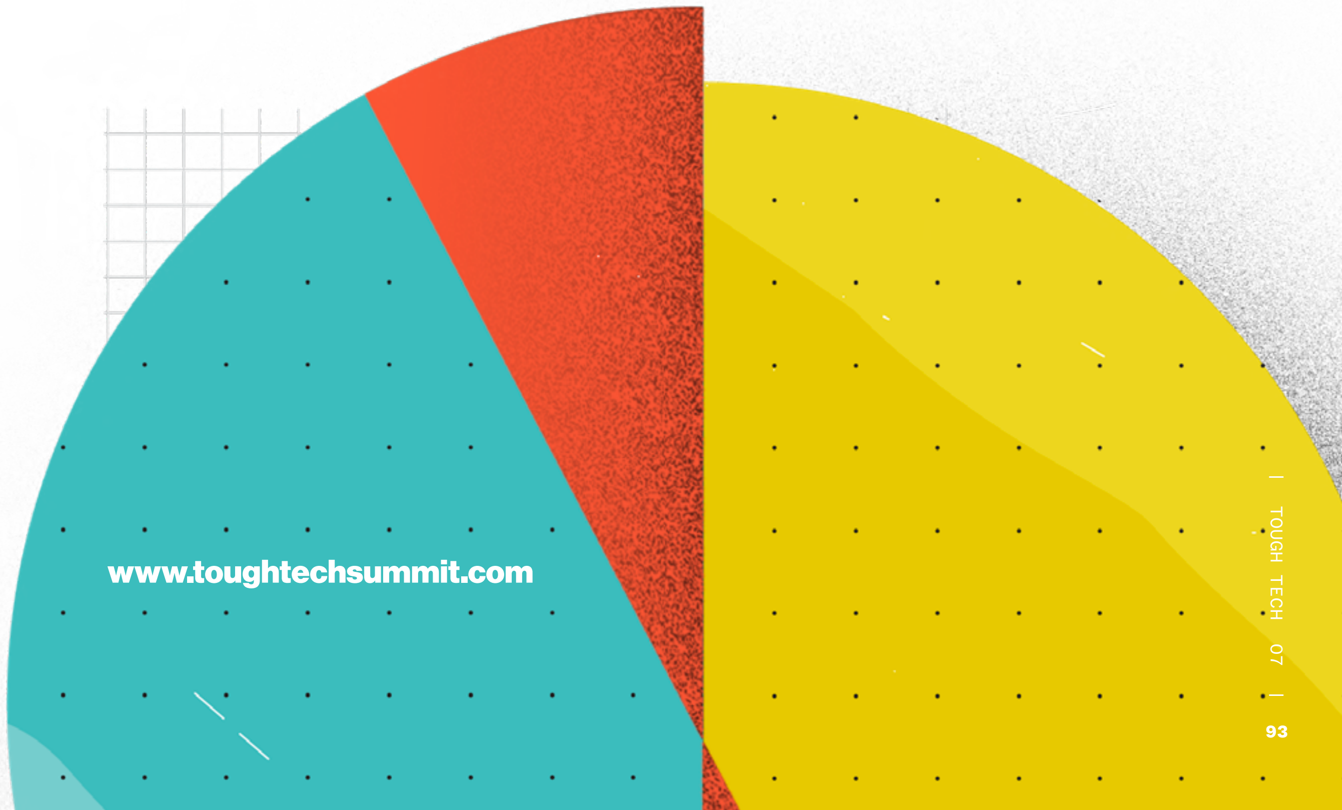
| CASE STUDIES | KEYNOTE TALKS | FOUNDER TALKS | and more.

Open to all and will feature a mix of keynote talks and sector-specific conversations focused on commercializing Tough Tech breakthroughs.

Day 2

| CASE STUDIES | KEYNOTE TALKS | FOUNDER PITCHES | and more.

Designed for an intimate audience of founders and investors. Conversations will focus on investment pathways and strategies. Attendees will also have the opportunity to view select founder pitches.



“

...A river gathered up of silver and gold,
Copper and lead. And later, when they saw these
Solid and shining below in splendid color –
How shiny and smooth they were – they picked them up,
Each in its outlines like a little pool
Shaped like the hollow that it left behind.
It struck them, they could melt the metal down
And make it run to the mold of whatever they liked,
Then they could draw it to however sharp
And slender a point you want, hammering, honing,
Giving them tools to fell the forest and
Rough-hew the wood with an ax and plane the planks,
Or bore with an auger or chisel through or gouge.
At first they tried no less with silver and gold
To make these things than with good rugged bronze –
In vain, for all the metals' strength gave in,
Not able to bear up under the same hard work.
So copper was prized more highly, and gold lay
Dull-edged and blunted in its uselessness.
Now copper lies – gold's stepped to the highest honor.

And so the roll of time brings change to all; What was once prized is now bereft of honor, Succeeded by another, once disdained...

LUCRETIUS
On the Nature of Things
60 BC

pg.10

→ Think of the cities your grandchildren will inhabit and you might imagine something futuristic — driverless transit systems, sensor — packed buildings, augmented reality, and androids that cater to a city dweller's every need. But these cities will not be defined by the innovations that move, entertain, and comfort; rather, they will be defined by the innovations within — the stuff that buildings are made of and the way those buildings are put together.

→ Global output of the construction industry is expected to grow to $15.5T by the end of this decade, and that pace will not slow. Buildings are and will continue to be central to human existence on this planet. They house us, provide places of employment, and for many are one of the largest investments and equity holders over the course of a lifetime. We now have the chance to invest in the technologies that could solve some of humanity's toughest problems in one of the world's largest industries; let's not miss it.

pg.52

→ Despite being largely invisible and embedded within our devices, semiconductors now form a system as essential as roads or the electrical grid. So many facets of our daily lives — not to mention our future prospects — rely critically on these glimmering objects and the streams of electrons alternately passing and not passing through their unimaginably thin channels.

→ There is no single replacement for the silicon transistor; nor is there just one bottleneck to resolve. If society is to continue to enjoy the rapid progress that has defined the information age, we will have to find more efficient ways to work with the processors we have, new processors tailored to the hardest calculations we face, and new materials for novel chips that can help processors communicate more quickly.

→ Even as Moore's law falters, the world has never needed it more.

→ One trend Feynman did not anticipate in 1959 was that once computing hit the bottom, it might strike out in a new direction entirely. We already use light to move data between continents and cities and recently between server racks in some data centers. For decades, streams of light laden with information have inched steadily closer to where the real action is happening: the motherboard.

→ In the coming decades, purpose-built chips matched to their application could slip into everything from appliances to clothing, literally weaving computation into the fabric of daily life. Screens will melt away as windows display the weather forecast and devices beam holograms into the air. Algorithms may even design the next generation of AI-boosting chips, accelerating the acceleration.

→ Imagining what future engineers will build with advanced versions of today's rudimentary technologies is a bit like asking a young Moore to speculate about what people might do with billions of transistors in their pockets.

THE ENGINE
Built by MIT

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