DISRUPTIVE INNOVATIONS VIII

Ten More Things to Stop and Think About

Citi GPS: Global Perspectives & Solutions

October 2021

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DISRUPTIVE INNOVATIONS VIII

Ten More Things to Stop and Think About

Kathleen Boyle, CFA
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In our new report, the eighth in our Disruptive Innovations series, we once again look at some of the leading-edge concepts across sectors and identify new products which could ultimately disrupt their marketplace. A few of the "new" concepts may not seem quite that new — e.g., alternative proteins and psychedelic drugs — but new technology and increased acceptance could make them game changers. Psychedelic drugs have been around in various forms since the 1950s, and despite showing promise at the time, regulation kept the class of drugs on the sideline. Today, their benefits are being explored in conditions such as treatment-resistant depression and anxiety. Plant-based alternative proteins are already changing the traditional "meat" households put on the dinner table, but new lab-grown cultured meat, with better taste and eventually a lower price, could become the next alternative protein.

Sustainability remains a big focus not only for governments, corporates, and investors, but also innovation. The battle on climate change has continued in earnest and the need to lower greenhouse gas (GHG) emissions has become even more of a global priority. Removing carbon dioxide for the benefit of the planet is explored in three ways: (1) nature-based solutions, including afforestation and reforestation; (2) enhanced natural processes, including land management and bioengineered plants; and (3) direct air capture (DAC) — the "alchemy of air," where machines capture carbon dioxide straight out of the atmosphere. In past issues, we have explored innovations in green transportation, including hydrogen-powered rail, autonomous vehicle networks, hyperloop, and electric vehicles. This year we look at the use of ammonia as a source to fuel jet engines. Although hydrogen and sustainable aviation fuels are further along as potential renewables solutions, most jet engines can be retrofitted to use ammonia, it is easily storable, and there is already an ecosystem for production and distribution in place. Finally, we explore how to close the recycling loop using de-polymerization methods that will cut down on plastic waste filling our landfills.

2021 has been a great year for innovation in healthcare. mRNA was largely unproven in 2020 despite decades of scientific research, but today has become one of the most powerful weapons against the pandemic. Given the rapid proof-of-concept for mRNA vaccines during COVID-19, we now know that mRNA can produce highly effective and safe vaccines — and COVID-19 vaccines could be just the tip of the iceberg.

Finally, a report on disruptive innovations would not be complete without looking at some new technology. The introduction and increasing popularity of non-fungible tokens (NFTs) coupled with the transition of retail into the metaverse highlights the blending of fintech with both consumer and gaming. Semiconductor manufacturing is on the verge of transforming from two-dimensional to three-dimensional architecture, which could increase the speed of chips by five-fold. And artificial intelligence could be coming to your next flight, protecting both your health and your safety.

Towards a More Sustainable and Digital Future

2024

Year 3D DRAM architecture is expected to become a reality in semiconductors

11%-45%

Alternative proteins as a % of total protein market by 2035

40%

Expected share of advanced plastic recycling technologies by 2030 (up from 10% in 2020)

$5bn-$6bn

Size of seasonal flu vaccine market targeted by mRNA vaccines

2

propulsion methods can use ammonia in aviation (gas turbines & fuel cells)

D2A & D2M

Next iteration of Direct-to-Consumer (DTC) is Direct-to-Avatar (D2A) & Direct-to-Metahuman (D2M)

7.1%

Direct Air Capture share of all carbon captured by 2070

3x

Increase in federal aviation rule violations in 2021 which may be prevented by robotic air marshals

NFTs

$37bn

Total market value of NFTs (non-fungible tokens) in 2021 vs. $2bn in December 2020

74%

of psychiatrists surveyed would prescribe psychedelics if FDA approved for treatment-resistant depression

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An Unprecedented Time for Innovative Companies

Adam Spielman
Managing Director, Citi Global Insights

Ever since the first *Disruptive Innovations* report was published back in 2013, Citi GPS has argued that the pace of technological change has been speeding up, and we have rejected the view put forward by some economists that real innovation had slowed down.

We believe our optimistic view has been vindicated in the past couple of years because there has been a further acceleration in the adoption of new technologies:

- The pandemic has accelerated (or started) the adoption of many innovations in many sectors.
- The more intense focus on tackling climate change has led more companies to change what they do at a faster pace than before.

On top of this, financial conditions have meant there has been a significant increase in the capital actually deployed by companies to make the innovations happen. This implies the rate of innovation is likely to remain high.

There is, however, one way in which the pandemic is likely to have worked against innovation, and that is the reduction in social interactions. There is now good evidence that remote work makes people more siloed and weakens their wider networks, even within their own firms. This is likely to hinder innovation because most innovation occurs through collective, distributed processes rather than in small tightly-knit groups.

The latest Citi GPS *Technology at Work v6.0* report argued that innovation will become more important in a post-production society, and that cities are likely to maintain their importance as innovation hubs despite all the talk of the death of distance in a constantly-connected world.

Overall, the step up in innovation in the past couple of years is a positive. However, if society, firms, and employees want to support it further, the evidence suggests individuals should return to work for at least part of the week, and also spend more time in cities.

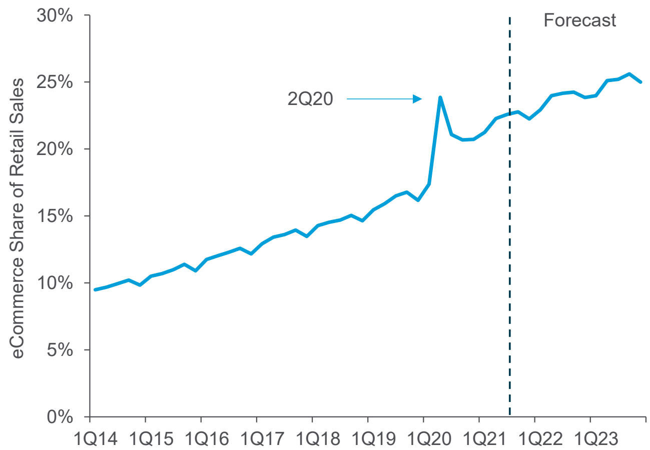
The Pandemic Has Accelerated (or Started) the Adoption of Many Innovations

It is often said the pandemic accelerated changes that were already taking place. We think in fact the reality is more interesting: In some sectors and with some innovations, existing trends were boosted; but in others, technologies that were barely used in practice have suddenly sprung into life.

The Pandemic Accelerated Adoption of Innovations in Some Already Flourishing Sectors

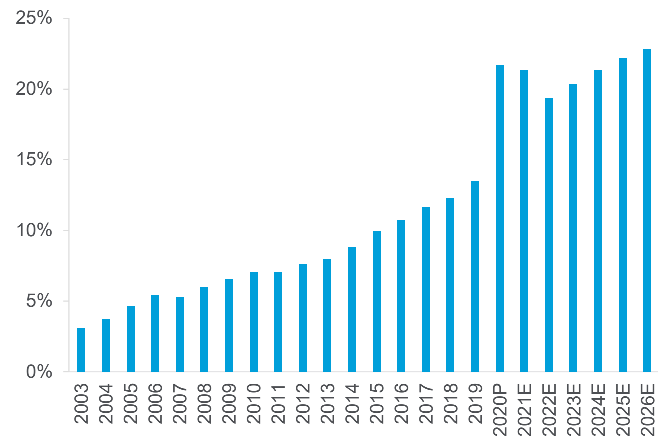
U.S. retail is a good example of a sector where the pandemic took an existing technology — e-commerce — and accelerated it. Figure 1 shows (1) that e-commerce was growing steadily before the stay-at-home orders; (2) that demand spiked in the second quarter of 2020 (when the stay-at-home orders were at their fiercest); and (3) that e-commerce now appears to be growing roughly as fast as before, but from a higher level than it otherwise would have reached.

Figure 1. E-commerce Share of Retail Sales Accelerated



Source: Citi Research

Figure 2. Global Online Gambling Penetration



Source: H2GC, Citi Research

Another example is financial services. We were already enthused about the prospects for fintech in 2019, with digital payments already growing at double digits in several markets. But the pandemic turned out to be a bigger catalyst for fintech than anything in the past decade. Online payments and e-commerce are now growing even more rapidly, while contactless interfaces are booming offline. One consequence is that U.K. ATM cash withdrawals have been running at about half their pre-pandemic levels.

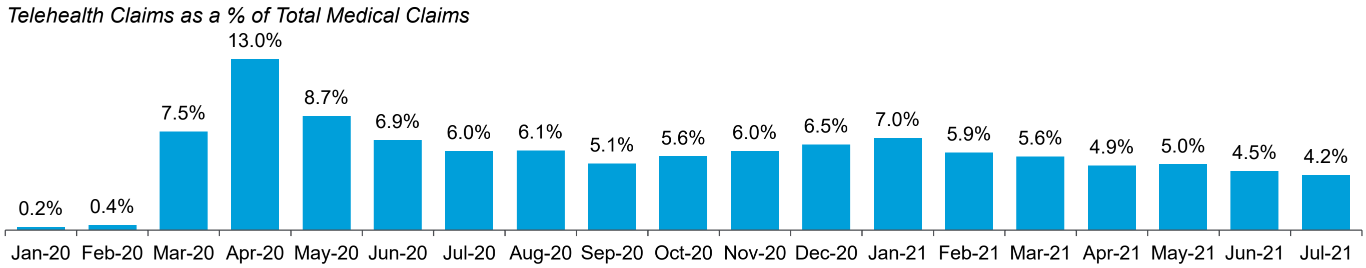
In Other Sectors, Remote Technology Was Rarely Used Pre-Pandemic

In other sectors, the pandemic caused the adoption of technologies that were more of a theoretical offer than a practical reality before the pandemic. Health and education are two important examples.

- **Health:** Before the pandemic, telehealth — i.e., attending a physician on-line instead of in person — was negligible in the U.S. However, that changed quickly as stay-at-home orders went into effect. During April last year 13% of all U.S. health claims were for telehealth treatment, according to Fair Health. The figure has fallen back since then, but now remains at a fairly steady 5% of all claims — more than 25x the pre-pandemic level. Experts we've spoken to at the Cleveland Clinic expect 30% or more of outpatient appointments will be conducted via telehealth after the pandemic is over, because it is so much more convenient for all parties, especially for chronic disease management, care coordination, and preventative care.[1] We are not surprised that investments in early-stage healthcare businesses have shot up since the pandemic (see Figure 3). For more on telehealth see the Citi GPS report *Disruptive Innovations VII*.

[1] See Citi Research, Key Learnings from Citi's Annual Cleveland Clinic Event, April 12, 2021.

Figure 3. While Telehealth Utilization Has Moderated Since the Height of the Pandemic, it Remains ~25x Higher than Pre-Pandemic



Source: Fair Health, Citi Research

- **Education:** Spending on digital educational technology (edtech) accounted for just 2.6% of education spending globally before the pandemic, according to HolonIQ. Tom Singlehurst, who leads coverage of the education sector for Citi Research, predicted that the sudden forced move to online learning would result in a full scale re-appraisal of the role technology can play. It is therefore pleasing to see how fast investments in edtech startups have grown (Figure 9). Tom and his team forecast total edtech spending will more than double from about $160 billion in 2019, to about $360 billion by 2024, implying growth of around 17% per year.

The Need to Address Climate Change Faster Is Also Increasing Demand for Innovations

A separate driver of acceleration in the last couple of years has been the increased sense of urgency on reducing greenhouse gas emissions.

We think several factors have caused the change in attitudes:

- The Environmental, Social, and Governance (ESG) movement has become more and more powerful, altering the way investors talk to companies, and hence how companies behave.
- The number of extreme weather events has increased — life-threatening heatwaves, droughts, and floods in many parts of the world.
- COVID-19 has shown that humanity can be knocked off course quite easily by small hiccups in the natural world.

The importance of the climate issue was confirmed by the 2021 IPCC report this August — the most pessimistic yet — which said the global temperature is likely to rise by more than 1.5°C by 2040.[2] The Secretary-General of the United Nations, António Guterres, described it as "a code red for humanity."

As a result, an increasing number of companies are changing their business practices, and again this has driven an acceleration in adoption of new technologies.

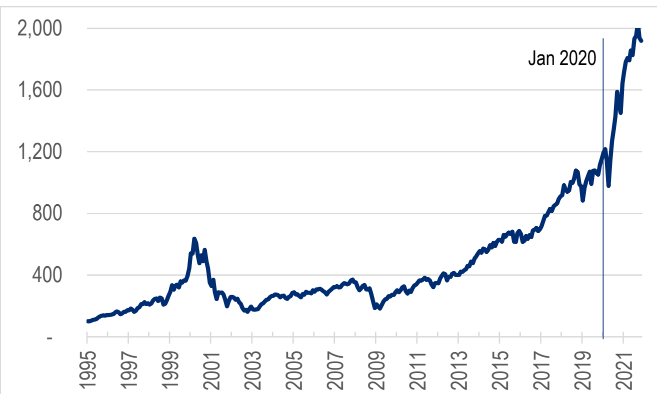
[2] See the IPCC website for the IPCC Working Group I report, *Climate Change 2021: The Physical Science Basis.*

More Capital Has Been Deployed by Companies to Make Innovations Happen

As we have said, the pandemic and the need to reduce emissions have increased the *deployment* of innovations. But we think there is a third driver of innovations — one of a completely different kind: the very unusual financial conditions that in turn have resulted in more cash being injected into disruptive startups.

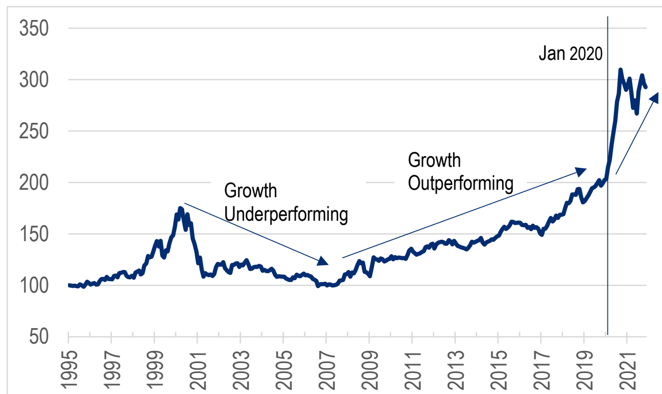
The key change is that financial markets are now favoring growth investments, relative to value, to a greater extent than ever before. This can be seen in Figure 4, which shows how rapidly the Nasdaq Composite Index has accelerated since April 2020. But Figure 5 is perhaps more important, because it shows the relative performance of growth versus value (when the line in Figure 5 is heading up growth stocks are outperforming, and when it's heading down they are underperforming). The chart shows that growth has outperformed since 2007, but there was a sharp acceleration starting in January 2020.

Figure 4. Nasdaq Composite Index – 1995 to Present



Source: Reuters

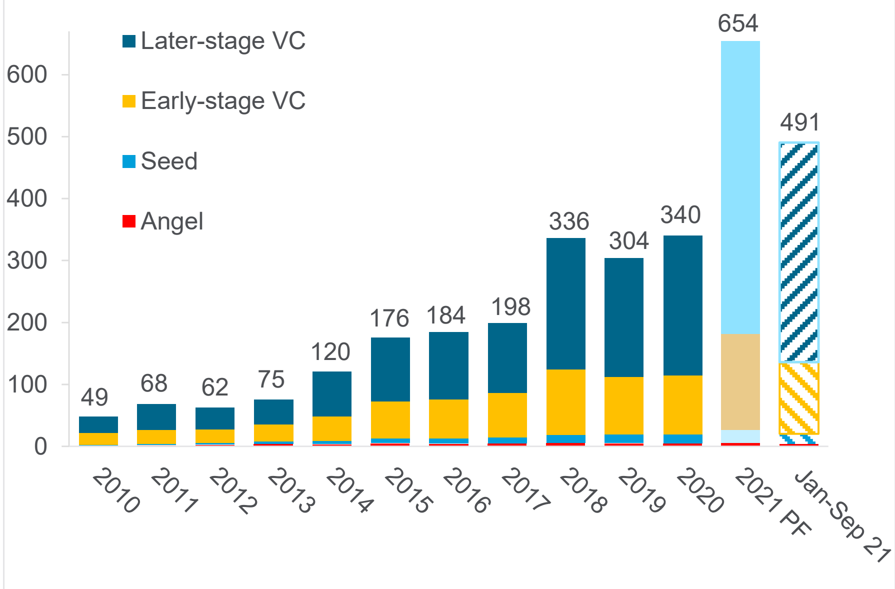
Figure 5. U.S. Growth Stocks Relative to Value – 1995 to Present



Source: Reuters

The level of quoted shares does not affect the real economy directly — but in technology the knock-on effects are important. Higher valuations in the public (secondary) markets for growth stocks drive investors to invest more cash in private (primary) markets, and this ends up being used by companies to make real investments on the ground. Figure 6 shows that more cash has been invested by venture capitalists (VCs) in private companies in the eight months to August 2021 than in any prior year — implying 2021 as a whole will be an extraordinary year.

Figure 6. Total Global Investments in Early-Stage Companies ($bn)



Source: PitchBook Data Inc.

In fact, the increase in value has come about because the average VC investment size has increased, as Figure 7 shows, and not because more investments have been made. But it still means that start-ups have more cash to develop and deploy than their predecessors did in previous years, implying the rate of innovation is likely to remain high in future years.

Figure 7. Total Global Investments in Early Stage Companies ($bn)

Dollar Invested ($ Blns)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021 PF	Jan-Sep 21
Angel	2.2	3.8	3.6	5.1	4.3	4.9	5.4	5.1	4.6	5.9	4.4
Seed	2.7	3.6	4.9	7.0	7.8	8.8	13	14	15	21.1	16
Early-stage VC	23	28	39	60	64	72	106	93	95	154.5	116
Later-stage VC	35	40	72	103	108	112	212	191	226	472.6	354
Private	**62**	**75**	**120**	**176**	**184**	**198**	**336**	**304**	**340**	**654**	**491**

Number of Deals ('000s)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021 PF	Jan-Sep 21
Angel	2.6	3.4	4.3	5.3	4.7	4.6	4.1	4.0	3.4	3.8	2.9
Seed	3.4	4.8	5.8	6.7	6.2	6.2	6.8	7.3	7.3	8.1	6.1
Early-stage VC	5.4	6.1	7.6	10.3	11.2	12.1	13.2	12.4	11.3	13.7	10.3
Later-stage VC	3.1	3.4	4.2	5.0	5.3	5.8	7.1	7.7	8.7	11.4	8.6
Private	**14**	**18**	**22**	**27**	**27**	**29**	**31**	**31**	**31**	**37**	**28**

Av Deal Size ($ Mlns)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021 PF	Jan-Sep 21
Angel	0.9	1.1	0.8	1.0	0.9	1.1	1.3	1.3	1.3	1.5	1.5
Seed	0.8	0.8	0.9	1.1	1.3	1.4	1.9	1.9	2.0	2.6	2.6
Early-stage VC	4.2	4.6	5.1	5.8	5.7	6.0	8.0	7.5	8.4	11.3	11.3
Later-stage VC	11.3	11.5	17.3	20.6	20.5	19.3	29.9	24.8	25.8	41.3	41.3
Private	**4.3**	**4.2**	**5.5**	**6.4**	**6.7**	**6.9**	**10.8**	**9.7**	**11.1**	**17.6**	**17.6**

Source: PitchBook Data Inc.

Of course it is possible that the public market's appetite for growth will decline again, and valuations both in the Nasdaq and in the private market will fall. This happened after the dot-com bubble burst in March 2000, when the Nasdaq Composite fell 78%.

But capital has been given to companies to make real investments, and that will be spent on creating and deploying innovations, whatever happens to valuations. The cash raised in 1997-2000, before the dot-com bubble burst, allowed technology, media, and telecoms companies to invest heavily in the following decade, putting in place much of the new economy as we know it today.

Change in Focus Sectors

When you look at the overall skew of investments by VCs, there have been some notable changes as a result of the pandemic. Figure 8 breaks down investments by aggregated sectors, and it shows that investments in all areas have grown. However, there have been particularly large increases in: (1) areas most focused on climate change (e.g., energy and materials); (2) fintech; and (3) healthcare.

Figure 8. Split of Global Investment in Early-Stage Companies by Industry Sector ($bn)

	2019	2020	2021 PF	Jan-Sep 21	CAGR
B2B	43	36	71	54	29%
B2C	77	75	130	98	30%
Energy	4	5	14	11	89%
Financial Services	17	18	53	40	77%
Healthcare	51	80	126	94	56%
Information Technology	107	118	250	187	53%
Materials and Resources	3	5	10	7	89%
Total	**302**	**336**	**654**	**491**	**47%**

Source: PitchBook Data Inc.

Edtech remains a small sector so it does not appear in Figure 8, but Figure 9 confirms investments have grown rapidly, especially in Business-to-Business (B2B) services — i.e. services aimed at helping schools, universities, and training facilities serve their students better.

Figure 9. Global EdTech Investments in Early-Stage Companies ($bn)

	2019	2020	2021 PF	Jan-Sep 21	CAGR
Education Services (B2C)	1.8	3.1	3.6	2.7	41%
Education Services (B2B)	0.6	0.5	2.3	1.8	105%
Educational Software	2.9	9.5	8.8	6.6	73%
	5.3	**13.1**	**14.8**	**11.1**	67%

Source: PitchBook Data Inc.

The Reduction in Social Interaction Is Likely to Lower Innovation Rates

Everything we have written about so far in this introduction suggests the pandemic has been positive for innovation. However, there is one way in which it is likely to be working against innovation — via the reduction in (weak) social interactions, an important factor in innovation.

Working from Home Makes Employees More Siloed, Even Within Their Own Firm

The most authoritative analysis of what happens when all employees in a firm work from home comes from an analysis of interactions by Microsoft's U.S. employees in the first half of 2020.[3]

The research was based on the calendars, emails, instant messages, and video and audio calls of almost all of Microsoft's 60,000 U.S. employees.[4] The analysis compared individual employees' interactions in the months before and after Microsoft's firm-wide work-from-home policy was put in place.

The statistics demonstrated that Microsoft's firm-wide remote work policy caused staff to become more siloed:

- Networks within siloes became more densely connected;
- Networks became more static, with fewer ties added and deleted per month; and
- Fewer bridges were made to weakly-connected areas.

In other words, research showed statistically that the shift to firm-wide remote work caused Microsoft's staff to spend more time with people they were already connected to by strong ties and less time with those connected by weak ties. This means Microsoft employees spent less time with those most likely to suggest new ways of thinking, even though they are (presumably) an especially tech-savvy group.

There was also a decrease in synchronous communication and an increase in asynchronous communication (in other words communication with a delay in it — for example email).

This is also important because asynchronous communication is better for conveying information and synchronous communication (such as a video call) is better for converging on the meaning of information. In-person and phone/video communication is more strongly associated with positive team performance than asynchronous communication.[5]

Evidence That Social Networks Drive Innovations

As we have said, most innovation derives from the sort of weak interactions — within firms and outside them — that has been diminished according to the Microsoft research we just quoted.

In the book *Where Good Ideas Come From: The Natural History of Innovation*, Steven Johnson explores the patterns that create innovations. Some types of environments seem to prevent innovations germinating; others to encourage them — and these are ones where ideas can be shared, debated, and evolved.

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[3] Longqi Yang et al., "The Effects of Remote Working on Collaboration Among Information Workers," *Nature Human Behaviour* (2021).
[4] The sample (n=1, 182) included all of Microsoft's U.S.-based staff, except for senior leaders and those who routinely handled especially sensitive data.
[5] Jose Maria Barrero, Nick Bloom, and Steven J. Davis, *60 Million Fewer Commuting Hours Per Day: How Americans Use Time Saved by Working from Home*, Becker Friedman Institute for Economics at UChicago, Working Paper No. 2020-132, September 15, 2020.

He lists 135 of the most important new ideas developed in the last two centuries — which we show in Figure 10 — and categorizes them on two dimensions:

- Whether the ideas were developed by either individuals or small teams within a single organization, or through distributed processes with large numbers of groups working simultaneously on different aspects of the same problem.
- Whether the inventors aimed to use them to be profitable or not. In Figure 10 we label this as "Market" and "Non-Market." Not surprisingly, most products — like nylon and the sewing machine — are in the Market quadrants, whereas all ideas — like natural selection and global warming — are in the Non-Market quadrants.

The key point is that about two-thirds of new products and scientific theories came about through distributed networks of large numbers of people working in different organizations, debating, and developing ideas, sometimes through formal meetings and sometimes by chance.

In some ways, this is unexpected. One might expect that in the heyday of capitalism, most innovations would come from single, profit-making companies. But Figure 10 shows this is wrong. It shows that some products that are now sold for a profit — for example the contraceptive pill and personal computers — were actually developed by distributed networks.

Figure 10. Major Innovations, 1800-2000. Small Group vs. Network; For Profit vs. Non-Market

Individual or Small Team (Market)

AC Motor
Air Conditioning
Dynamite
Gatling Gun
Mason Jar
Nylon
Programmable Computer
Revolver
Tesla Coil
Transistor
Vulcanized Rubber

N=11

Distributed Network (Market)

Airplane
Automobile
Bicycle
Calculator
Contact Lenses
Electric Motor
Electricity
Engine
Helicopter
Induction Motor
Internal Combustion
Jet Engine
Laser
Lightbulb
Locomotive
Motion Picture Camera
Moving Assembly Line
Personal Computer
Photography
Plastic
Radio
Refrigerator
Sewing Machine
Steel
Tape Recorder
Telegraph
Telephone
Television
Typewriter
Vacuum Cleaner
Vacuum Tube
CVR
Washing Machine
Welding Machine

N=35

Individual or Small Team (Non-Market)

Absolute Zero
Archaea
Atomic Theory
Benzene Structure
Blood Groups
Bunsen Burner
Cell Nucleus
Continental Drift
Cosmic Radiation
CT Scan
Double Helix
$E = MC^2$
Early Life Simulated
Earth's Core
Ecosystem
Electrons in Chemical Bonds
General Relativity
Heredity
Hormones
Liquid Engine Rocket
Natural Selection
Neutron
Nitroglycerine
Radiometric Dating
Rechargeable Battery
Special Relativity
Spectroscope
Stethoscope
Superconductors
Uncertainty Principle
Uniformitarianism
Universe Expanding
World Wide Web
X-Rays

N=34

Distributed Network (Non-Market)

Artificial Pacemaker
Atoms Form Molecules
Cell Division
Chloroform
Computer
DNA (as Genetic Material)
EKG
Electron
Endorphins
Enzymes
GPS
Internet
Liquid-Fueled Rocket
Mitochondria
Modern Computer
Oncogenes
Plate Tectonics
Punch Card Programming
Restriction Enzymes
RNA Splicing
Suspension Bridge
Universe Accelerating
Vitamins
Anesthesia
Aspirin
Asteroid K-T Extinction
Atomic Reactor
Background Radiation
Braille
Cell Differentiation
Chemical Bonds
Cosmic Microwave
Cosmic Rays
DNA Forensics
Gamma-Ray Bursts
Genes on Chromosomes
Germ Theory
Global Warming
Graphic Interface
Infant Incubator
Krebs Cycle
MRI
Neurotransmitters
Nuclear Forces
Oral Contraception
Penicillin
Periodic Table
Quantum Mechanics
Radar
Radioactivity
Radiocarbon Dating
Radiography
RNA (as Genetic Material)
Second Law
Stratosphere

N=55

Source: Steven Johnson, *Where Good Ideas Come From*

What Does This Mean for Working From Home?

We think this is directly relevant to the question many people are asking now around "returning to work."

The evidence does not say it is impossible to innovate in organizations where everyone is working from home. Some innovations are created by very small groups of people, or even individuals, and small tight-knit groups can continue to function well over video calls.

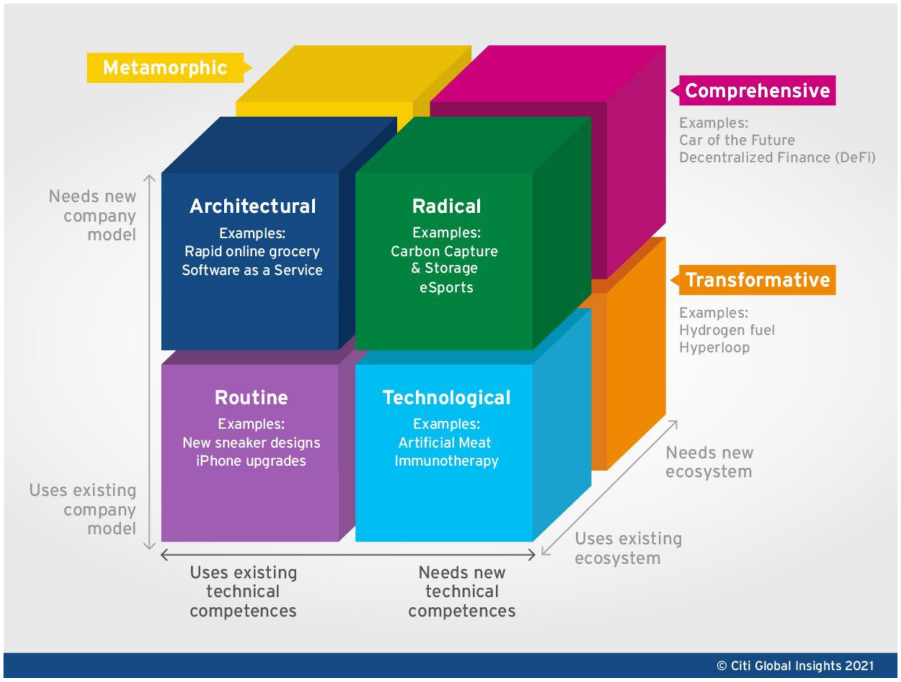
But the research at Microsoft shows that remote work makes people more siloed and weakens their wider networks, even within their own firms. More generally, weak networks atrophy if people stay away from offices and cities. Fewer unexpected meetings take place — both within companies and institutions, and within wider and weaker networks — and most innovation relies on this kind of exchange.

Overall, there has clearly been a step up in innovation in the past couple of years, which is positive in all sorts of ways. But the historic evidence suggests individuals would probably do best by returning to their work places and cities if society, firms, and employees want to support innovation further. And if firms want to encourage mixed mode work — partly in the office and partly at home — then this needs to be carefully planned to maximize out-of-silo communication as much as possible.

Ten More Things to Stop and Think About

The core of this report is about the ten new disruptive innovations. We believe it is well worth considering them in the light of the Citi Innovation Cube, which we recently introduced.[6] This is a tool for analyzing innovations and helping investors and other observers think about the issues surrounding innovations. What are the risks? What are the hurdles? And what needs to happen for the innovation to become established?

Figure 11. The Citi Innovation Cube



Source: Citi Global Insights

What is the Citi Innovation Cube?

The Cube recognizes that innovations vary along three dimensions:

1. **Technology:** *Can the companies use existing technical competences or do they need to develop new ones?* For a traditional auto company, developing the next gasoline engine builds on existing competences; developing an all-electric car requires it to master completely new ones.

2. **Company model:** *Can the companies continue to use their existing business models, or do they need new ones?* If a software company is moving from selling licenses to use software, to selling software "as a service," that requires a re-arrangement of the company business model but not a fundamental change in technology.

[6] The Citi Innovation Cube is an evolution of an idea created by Gary Pisano in *Harvard Business Review* (June 2015). He categorized innovations on two dimensions, but we think more insights can be created by thinking in three.

3. **Ecosystem:** *Does the innovation require a new ecosystem to support it?* Software-as-a-service fits into the existing infrastructure; by contrast, the Car of the Future needs a new eco-system including new charging stations, new types of workshops and mechanics, and new types of regulation and insurance. Most ecosystems are open, but some are closed.

There are significant consequences associated with being in different parts of the Cube:

- **New company models:** There are plenty of innovations that rely on new business models, not new technologies — and with these, speed to scale is often the most important determinant of success. The central question is whether the new company model can (eventually) become profitable.

- **New technical competences:** Where innovations involve genuinely new technologies, competitive advantage revolves around how well a company can get the new technology to work and at what cost.

  It is important to separately analyze (1) the potential sales of the technology; and (2) the economic potential that the technology enables — for example, to differentiate between the size of the market for 5G telecom equipment, and the new economic opportunities that 5G will produce.

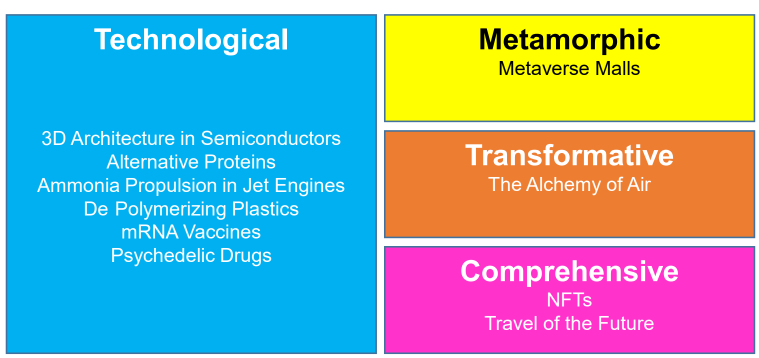
- **New ecosystems:** Where an innovation requires a new ecosystem, it is inevitably more difficult for the innovation to achieve commercial success, as many different actors have to move, all at roughly the same time. In addition, it is much, much more difficult to predict what will happen, as many factors are interacting with each other. However, when a new ecosystem does emerge, the consequences are likely to be profound.

Where Do the Ten Disruptive Innovations Fit in the Cube?

Six of the ten disruptive innovations, as discussed in the report, can be classified as "Technological." As we have said, the central question with these is whether the technology will really work as well as we think.

However, four of them need new ecosystems — and that makes them more ambitious. On one hand, there is always the risk that ecosystems don't evolve in the way we think. On the other hand, if they do evolve, the implications are likely to be much more substantive.

Figure 12. The Ten Disruptive Innovations, Classified According to the Cube



Source: Citi Research

As is always the case, it is possible to debate some of the classifications. For example, in Figure 12, we have categorized:

- The Metaverse Mall as a Metamorphic Innovation, because we would argue that while each metaverse requires new ecosystems of virtual shops (to drive visits) and a new business model, they do not really require new technical competences.
- Ammonia jet propulsion as a Technological Innovation because it does not require a significant new ecosystem (the fertilizer industry already creates plenty of ammonia, and it can easily be moved to airplanes in tankers).
- Carbon capture as a Transformative Innovation because, to become a reality, it needs breakthrough technical improvements and a new ecosystem in which to store the CO_2.

In reality, each axis of the Cube is a continuum, not an “either/or” category.

That said, we think the Cube is a useful tool, and the classifications shown in Figure 12 are relevant. The risks with innovations on the left of the chart are around the new technology — can it be made to work? The risks with the innovations on the right of Figure 12 are much greater (with a corresponding increase in the rewards) because to be successful, whole ecosystems have to evolve.

3D Architecture in Semiconductors

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We believe the adoption of 3D architecture will be a meaningful disruptive innovation in the semiconductor industry in that it will fundamentally change the structure of semiconductors from a planar (2D) to a 3D structure. This change could not only generate as much as a 5x speed improvement over comparable 2D solutions, it will also significantly affect the process for fabricating semiconductors in the future.

We project the adoption of 3D architecture will increase across several different semiconductor products and will drive technology migration in the future. In particular, we believe that 3D architecture, which has seen significant adoption in NAND space already, will be increasingly adopted in DRAM and logic products as well.

DRAM (dynamic random access memory) is used as a computer's main memory and stores data in a memory cell consisting of a capacity and a transistor.

In DRAM, the adoption of 3D architecture is expected to take place in stages. The first area of adoption is expected in HBM (high bandwidth memory), which stacks chips on other chips and connects them using a TSV (through-silicon via) method. HBM is used for artificial intelligence (AI) and high performance computing applications. The second area of adoption is likely to be seen with innovations in semiconductor materials such as hafnium oxide (HfO2) and niobium (Nb). Lastly, we expect to see changes in the architecture itself, migrating from today's 2D architecture to the new 3D architecture.

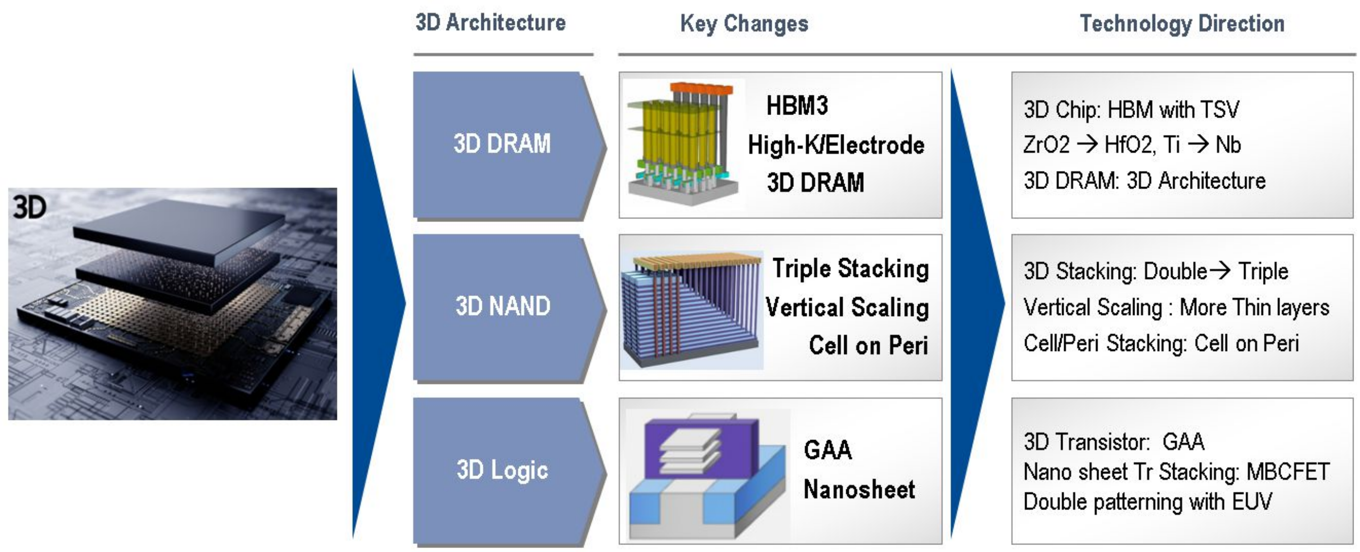
NAND is a type of storage technology that does not require power to retain data, e.g. a memory chip in a mobile phone or a flash drive.

In NAND, we expect 3D architecture will develop further with (1) the additional stacking of layers with COP (cell-on-peri) technology and (2) the adoption of double/triple stacking. Until now, some companies have only employed a single stacking method, but due to increasing difficulties in the etching process as the number of stacked layers increases, we expect they will begin adopting double stacking method from 176-layer 3D NAND products by the end of 2021.

Logic semiconductors process digital data for the purpose of controlling the operation of electronic systems.

Lastly, in logic semiconductors, we believe the transition to 3D architecture will begin in earnest with the shift in the architecture of transistors from multi-gate FinFET (fin field-effect transistor) to GAA (gate-all-around) technology. GAA is expected to be widely adopted from sub-3nm (nanometer) nodes, and we expect market leaders to use MBCFET™ (multi-bridge channel field-effect transistor) architecture to vertically stack nanosheets for chips under 3nm. We anticipate adoption of 3D architecture will begin in the second half of 2022 for logic and 2024 for DRAM.

Figure 13. 3D Architecture Direction: 3D DRAM + 3D NAND + 3D Logic

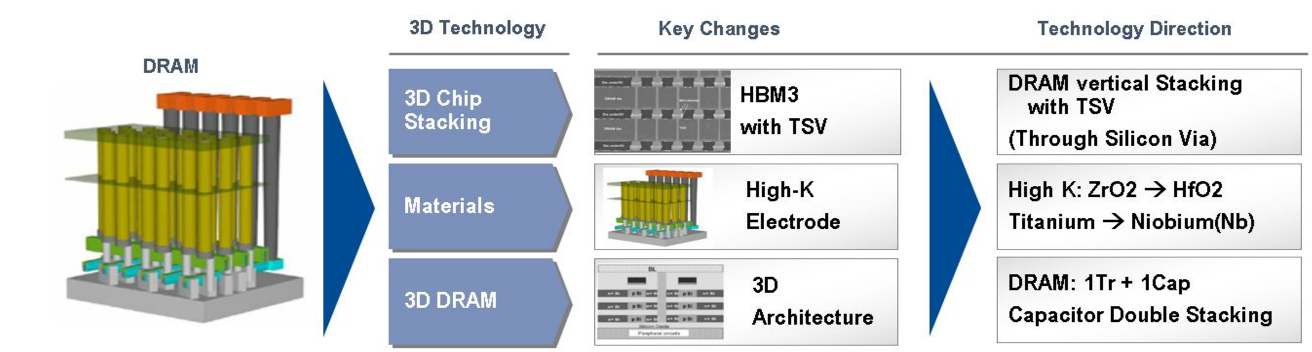


Source: Citi Research

3D DRAM: Vertical Stacking

Unlike in NAND, the architecture in DRAM has remained in a 2D structure until now. HBM (high bandwidth memory) technology that utilizes the TSV (through-silicon via) method — the first step in 3D architecture — has already been deployed. But the HBM architecture, which achieves 3D architecture by stacking 2D DRAM chips on one another, differs structurally from that of 3D NAND, which stacks layers within a DRAM chip. Despite the limited deployment of the HBM structure, we consider HBM as an intermediary step to eventually reaching 3D DRAM architecture. In addition, we believe innovations in materials will continuously take place in High-K dielectric and metal gate electrodes, especially for sub-1αnm chips, to enhance permittivity and conductivity. While we believe the DRAM structure will eventually evolve into a 3D structure, similar to 3D NAND, we project the order of development will be (1) HBM, (2) material innovation, and (3) architecture change to 3D DRAM.

Figure 14. DRAM Technology Direction



Source: Citi Research

3D architecture in the DRAM space is still in a nascent stage.

Contrary to 3D architecture in other applications, including NAND, the concept of 3D structure in DRAM is relatively unknown to the market given the technology's nascent stage. The direction we see in the DRAM 3D development process will drive the transformation of chip architecture from a 2D to a 3D structure.

Progression of DRAM Process Sizes

2008 – 40nm-class (4x) – 49nm-40nm
2010 – 30nn-class (3x)– 39nm-30nm
2011 – 20nm-class (2x) – 29nm-20nm
2016 – 10nm-class (1x)– 19nm-10nm
2020 – 1xmn (Gen1) – 19nm-17nm
2020 – 1ymn (Gen2) – 16nm-14nm
2020 – 1zmn (Gen3) – 13nm-11nm
R&D - 1αnm (Gen4)
R&D - 1βnm (Gen 5)
R&D - 1γnm (Gen6)
R&D - 1δnm (Gen7)

While DRAM makers can migrate beyond the 10nm node process size up to 1γnm (1-gamma process node) using an EUV (extreme ultra violet) scanner, beyond1δnm (1-delta node) DRAM producers are highly likely to try altering the architecture of DRAM chips to a 3D structure to achieve further node migration. Transformation to a 3D DRAM structure will progress in two key directions. The first direction will be the method of reducing chip size by using a PUC (peri-under-cell) structure, similar to the COP (cell-on-peri) structure being adopted in 3D NAND architecture. The second direction is rotating current the DRAM architecture by 90° to achieve a 3D DRAM structure, thereby creating a structure that highly resembles 3D NAND structure. This method maintains DRAM's current 1Tr1Cap (one transistor, 1 capacitor) structure, but instead of positioning capacitors vertically, it positions them laterally to enable stacking. The method stacks transistors vertically, as in GAA (gate-all-around) technology, while repositioning capacitors laterally,

The structure of 3D DRAM is expected to be similar to 3D NAND in that it creates dummy layers first and then etches the dummy layers to create cells. However, in forming capacitors, 3D DRAM is expected to perform repeated oxide and SiGe (silicon-germanium) depositions, rather than nitride deposition, and then use a peroxide-type etchant for etching. Due to increased difficulties in the etching process, we expect 3D DRAM structure will begin to be adopted in earnest from nodes more advanced than 1δnm.

3D NAND: Multiple Stacking + Cell-on-Peri Technology

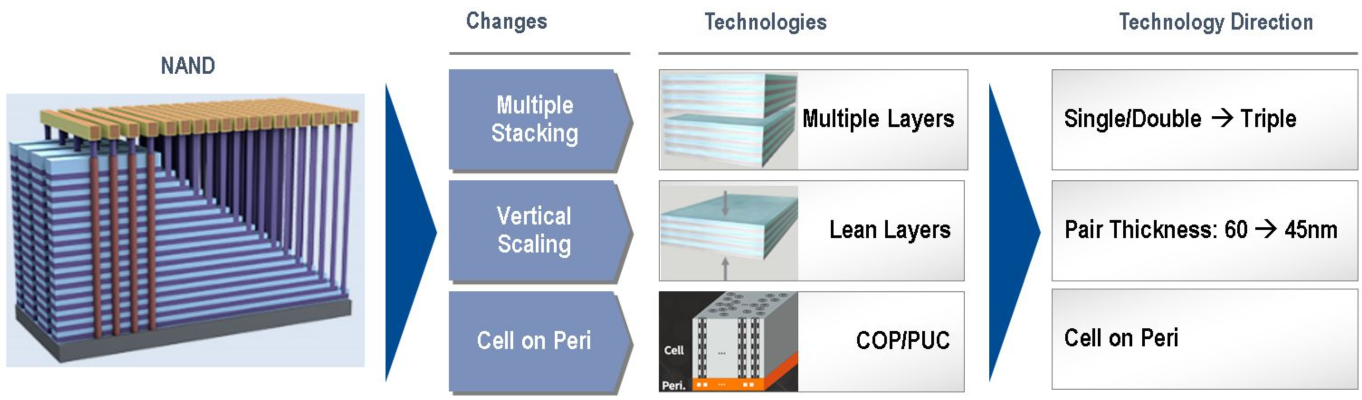
In NAND, we project facilitated adoption of 3D NAND structure. 3D structure in NAND has gone through continuous and rapid increases in the number of layers; current 72-92 layers are expected to migrate to 128-176 layers in 2021, and reach as high as 200 layers after 2021.

The first direction in NAND technology we expect is the increased adoption of multi-stacking technology. Market leaders, some of which have relied only on single stacking in the past, are expected to begin adopting double stacking from 176 layers, while other NAND producers are likely to adopt triple stacking amid continued competition to increase the number of layer stacking.

The second direction we expect is vertical scaling. With the number of its layers exceeding 100, 3D NAND has shifted from nanoscale to microscale, and has begun to be affected by gravity. This has forced producers to take gravity into consideration in the fabrication process. Mounting pressure on the lower layers of 3D NAND can result in the collapse of the structure, which in turn can negatively affect the characteristics of NAND chips and potentially deteriorate the quality of memory chips.

In addition, dry etching is used to etch a large number of holes in 3D NAND, but due to the increased depth of holes, it has become increasingly complicated to etch holes uniformly. We believe NAND producers will shift towards reducing the thickness of each layer in the deposition process in order to lower the total height of the structure, and we expect pair thickness to be reduced from 60nm to 45nm.

Figure 15. 3D NAND Direction: Multiple Stacking + Vertical Scaling + Cell on Peri



Source: Citi Research, Samsung Electronics

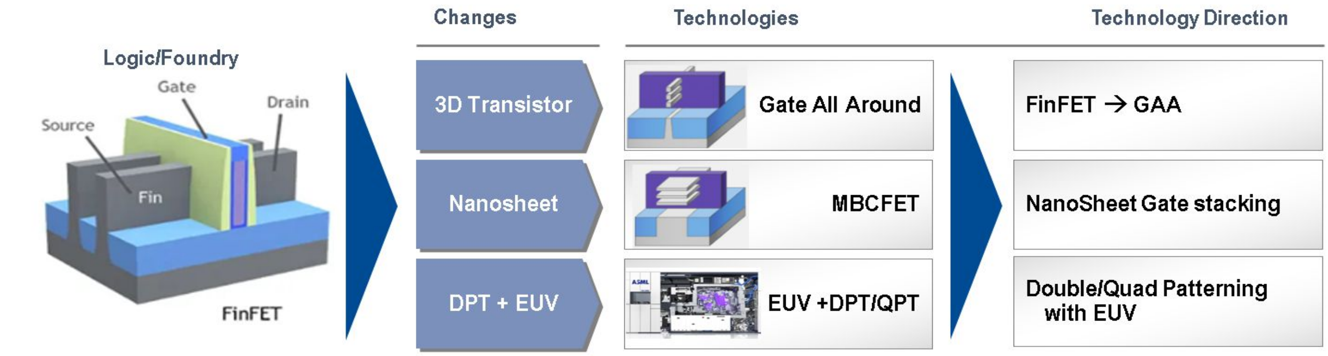
The third direction we anticipate is the COP (cell-on-peri) method. While only a few companies have adopted COP, we expect more to adopt COP technology from 176 layers. We believe adoption of the new technology will result in the reduction of chip size by 20%-30%.

3D Logic/Foundry: GAA + Nano Sheet + EUV

3D structure is being introduced rapidly in logic products as well. While current FinFET (fin field-effect transistor) technology, which uses EUV (extreme ultraviolet lithography) in the 7nm and 5nm fabrication process, remains the mainstream 3D technology, we expect 3D structures will migrate to GAA (gate-all-around) technology in earnest from 3nm onwards. We believe the migration will take place in through adoption of (1) 3D transistors, (2) nanosheet technology, and (3) double patterning technology (DPT) and EUV lithography.

A typical GAA transistor takes the form of a thin and long nanowire. However, a channel needs to be as wide as possible in order to allow a large amount of current to flow through it, and the small diameter of the nanowire makes obtaining this higher current flow difficult. To overcome this, market leaders have developed MBCFET™ (multi-bridge channel field-effect transistor), an optimized version of the GAA transistor. MBCFET™ increases the areas that make contact with gates by aligning wire-formed channel structures as 2D nanosheets, which enables simpler device integration as well as increased electric current. MBCFET™ is a competitive transistor structure in that it not only includes the means to mitigate the short-channel effect thanks to the GAA structure, but it also increases performance by expanding the channel area.

Figure 16. Logic/Foundry Technology Direction: 3D Transistor + Nanosheet + EUV with DPT



Source: Citi Research

We expect the adoption of 3D structure will have material impacts in the semiconductor market. In memory, we anticipate increased adoption of 3D DRAM and 3D NAND will lead to more complex fabrication processes. In logic, we believe the shift to 3D architecture with EUV will further strengthen market leaders' production edge and facilitate consolidation in the semiconductor market.

Wider adoption of 3D structure will lead to increased technical complexity in the fabrication process for semiconductor chips. In DRAM, the order of technological development is expected to be adoption of HBM (high bandwidth memory), innovative semiconductor material, and 3D DRAM architecture. We anticipate increased difficulties in the fabrication process will strengthen the technological barrier of incumbent market leaders and consolidate their leading positions.

We expect the technology to migrate from FinFET to GAA and nanosheet, a shift we believe is likely to produce a winner-takes-all situation in the semiconductor space. In particular, the technology gap between companies equipped with EUV and 3D structure technology and companies that lack these technologies will widen further, consolidating the market position of technology leaders.

Alternative Proteins

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Almost all meat alternatives currently come from plants, but it is now becoming possible to grow cultured meat in labs. We think alternative proteins is a sector with great potential, in terms of economics and because livestock farming creates many ESG issues. However, it is important to realize that most consumers currently buy alternative meat mainly because of the perceived benefits around taste, health, and (potentially) price — not for environmental reasons.

Plant-Based vs. Cultured Meat

There are three technologies involved in creating meat alternatives:

- **Plant-based alternatives:** use "biomimicry" to create products that taste, smell, and look like meat, but are much kinder to the environment, animals, and people.
- **Fermentation:** uses yeast to transform products (e.g., making beer), or to create new ones (e.g., meatless meatballs). Precision fermentation uses fungi to make specific proteins (e.g., insulin), enzymes, flavor molecules, vitamins, and fats, and these in turn can be used to help improve plant-based or cultured products.
- **Cultured meat:** can be thought of as lab-grown. It is "meat" produced directly from cells, using the same biological processes that occur when animals build muscles.

These three technologies can be combined. Cultured meats and fats can provide better flavor, but plant-based meat provides bulk at a lower cost. Some companies use fungi to create products to add flavor and meatiness to otherwise plant-based meat.

Plant-based meats (with or without fermented additions) are already quite widespread, accounting for a little under 3% of the North American and European fresh meat market in 2020.

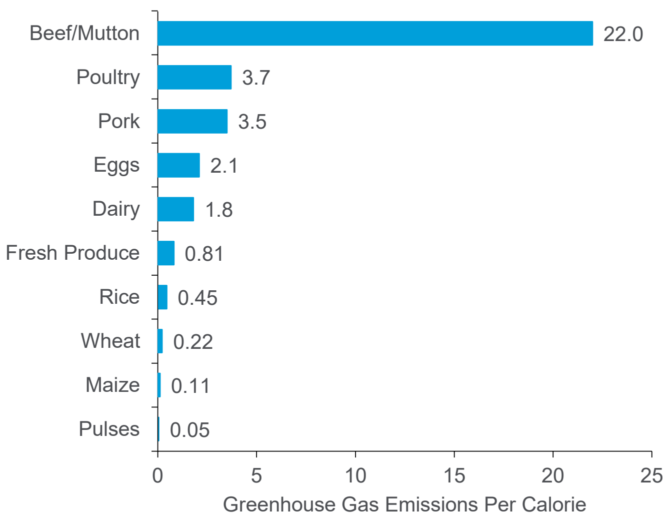
By contrast, cultured meat is nascent only. Most companies are still developing the technology and only a few have begun to scale up production. In Singapore, it is now possible to buy "chicken nuggets" made from a mixture of cultured and plant-based meat. One of the difficulties is that cultured products need regulatory approval for sale to consumers, and there is not a single country that has put a clear regulatory pathway for them in place — even Singapore has given only ad hoc approvals.

There Are Significant ESG Benefits

Replacing livestock farming would bring many benefits from an environmental, social, and governance (ESG) perspective because the livestock industry is responsible for:

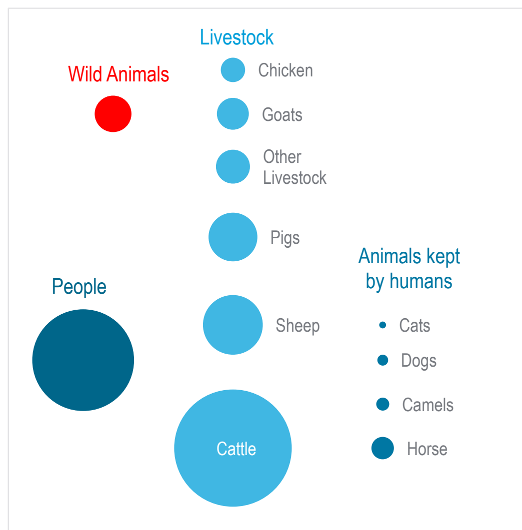
- **Emissions and water usage:** A disproportionate amount of greenhouse gas emissions and water usage are related to the livestock industry.
- **Deforestation and biodiversity loss:** The expansion of pasture land for cattle accounts for ~40% of tropical deforestation, or about 2.1 million hectares per year.[7]
- **Serious concerns about animal welfare:** The cheapest meat comes from intensive farming that encourages rapid animal weight-gain through growth hormones and non-traditional foods. Large-scale feed-lot farms contain thousands of animals held in pens that prevent them from moving freely.
- **Zoonotic diseases:** Intensive farming increases the risk of disease developing in livestock or poultry, and then spreading to humans.
- **Inappropriate antibiotic use** which increases the risk of antibiotic resistance.

Figure 17. Typical Greenhouse Gas Emissions per Calories by Food Type (gCO₂/kcal)



Source: Our World in Data, Clarke and Tilman (2017), Citi GPS *Feeding the Future*

Figure 18. Wild Animals vs Humans and Animals Used by Humans – Current Biomass Globally



Note: Terrestrial animals only.
Source: UK National Food Strategy Plan

It is vital to realize that ESG benefits motivate only a small minority of consumers to buy the product. Growth has to come from mainstream consumers, and they are generally motivated most by what they believe benefits them: taste, health, and (potentially) cost.

According to a recent global Euromonitor study, about 36% of consumers buy plant-based meat because it makes them feel healthier, compared with about 20% who do so to reduce their environmental footprint or to promote animal welfare.

[7] Florence Pendrill et al., "Agriculture and Forestry Trade Drives Large Share of Tropical Deforestation Emissions," *Global Environmental Change* 63 (May 2019): 1-10.

In the U.S. specifically, it seems that environmental and animal welfare issues are less important motivations than in Europe. A Mintel survey of U.S. consumers found that concerns about the environment and animal welfare were a driving consideration for only 13% and 11%, respectively, of those who eat plant-based proteins.[8] The main reasons, according to the survey, for choosing plant-based food are clearly taste (52%) and health (39%).

There is also substantial confusion over the true environmental impact: 44% of U.S. consumers believe plant-based meat is better for the environment, 38% believe it is the same, and 23% believe it is worse.[9]

We Believe Lower Prices Could Lead to a Tipping Point

We believe that for true mass-market acceptance, alternative meats need to (1) match traditional products on taste, (2) preferably beat them on price, and (3) have a clear advantage in terms of perceived health benefits.

- **Taste:** It is already hard to tell the difference between many plant-based burgers and traditional ones, partly because they are typically consumed with other strongly-flavored ingredients and condiments, and because the texture is easy to control.[10]
- **Price:** Currently many plant-based burger patties are 50% to 100% more expensive than regular, mass-market meat. However some of the leading companies say they will be price competitive in two to three years.
- **Health:** Perceptions of what is healthy have changed dramatically over the years. We think it is quite possible that perceptions of the health advantages of meat alternatives could increase materially.

The Biggest Risks Are Around Health and Regulation

However, it is also quite possible perceptions of health could move against plant-based meats. One of the most important mega-trends in the consumer sector is the desire for "natural" and it is easy to argue that plant-based meat is not natural.

Plant-based butter — otherwise known as margarine — used to be widely considered as healthier than butter, for example, but it is not anymore. As a result, sales have declined even as sales of butter (which is much more expensive) have risen.

For cultured meat, there is also a major risk around regulation. Alternative meat not only threatens farmers, it also threatens entire rural communities because about three-quarters of farmland globally is devoted to livestock and pasture. Given the importance of rural communities in most political systems, we see plenty of incentives for governments to go slow on giving regulatory approval for cultured products.

[8] "Taste Is the Top Reason US Consumers Eat Plant-Based Proteins," Mintel, February 15, 2018.
[9] See Citi Research, Citi Consumer Survey on Plant-Based Meat, April 27, 2021.
[10] About 40% of beef consumed globally is ground, used in foods such as lasagna, nachos, and dumplings.

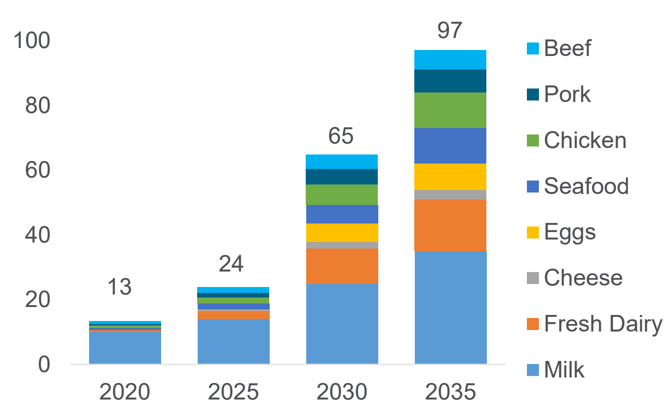
Alternative Meats Could Take a Big Bite Out of the Market

In 2020, retail sales of alternative meats were about $3.9 billion in North America and Western Europe combined, roughly equally split between the two.[11] This was up 28% on 2019. In a normal year, food service sales (for example, sales in fast food chains) add another 75% to volumes, but 2020 was not a normal year. This all means that less than 3% of fresh meat came from alternatives. However, the market is growing fast: In the first quarter of 2021, retail sales of alternative meats in the U.S. were up 60% on the same period a year earlier.

We have seen long-term forecasts by two consultancies, both saying they expect strong growth in alternative proteins on a 15-year view. But there is a wide range of estimates, which shows just how difficult it is to forecast this category over the long term.

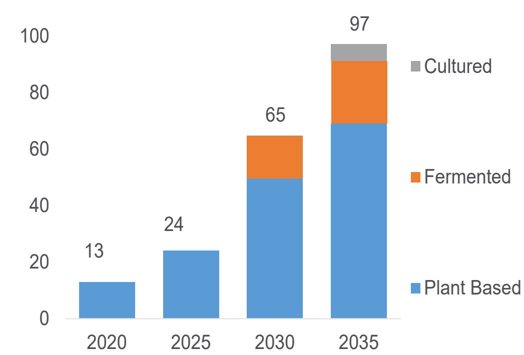
- Figure 19 shows the base case forecast from BCG and Blue Horizon. They forecast that by 2035, about 11% of all protein consumption will come from alternatives. Of this total, they forecast that 56% of the volume (by weight) will be dairy products but that meat and seafood will exhibit faster growth. This forecast equates to about $290 billion in retail sales for alternative proteins, implying about 20% compound growth during the next 15 years. Figure 20 cuts the same forecast by technology, and what is striking is that these companies expect cultured products to contribute only 6% of total volumes in 2035.
- A separate report by Kearney focusing only on meat gives quite a different outlook. It says that by 2035 cultured meat will effectively generate the same sales as plant-based meat, with the combination representing about 45% of the global meat market.

Figure 19. BCG/ Blue Horizon Base Case Forecast for Alternative Proteins (Millions of Metric Tons)



Source: BCG/ Blue Horizon

Figure 20. BCG/ Blue Horizon Base Case Forecast for Alternative Proteins (Millions of Metric Tons)



Source: BCG/ Blue Horizon

[11] Euromonitor is the source for all the data in this paragraph. To put the $3.9 billion in context, retail sales for alternative milk were about $6 billion in the same geographies, and about $7 billion for margarine.

What About the Companies and Farmers on the Wrong Side of This?

Many meat processor companies have addressed the threat from alternative meat by taking stakes in some start-ups. However, none has sought to truly transform itself into an alternative meat company.

We believe alternative meats also threaten commercial farmers who receive little subsidy and who produce undifferentiated mass-market meat that ends up in minced/ground products like burgers and chicken nuggets.

However, many farmers — especially in Europe — rely entirely on subsidies, and over time we expect that where subsidies are paid, the emphasis will switch further toward environmental goals and away from production.[12]

[12] In Europe, most livestock farmers make a loss from agriculture, selling their animals for less than the cost of the inputs.

Ammonia Propulsion in Jet Engines

Fueling Sustainable Aviation

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Emissions resulting from air travel are increasingly becoming a focus in society. Although more nascent than alternatives such as hydrogen and sustainable aviation fuels, ammonia propulsion could join a list of possible solutions for the aviation industry. An ammonia-fueled jet engine can be easily adapted from currently available engines and ammonia is much easier to store as a liquid than hydrogen. Additionally, ammonia is already produced at enormous scale due to its high usage in agriculture around the world. However, current ammonia production is primarily derived from hydrocarbon — so it is not green — and there are still concerns about ammonia's toxicity and the challenges of getting new technology in aviation certified.

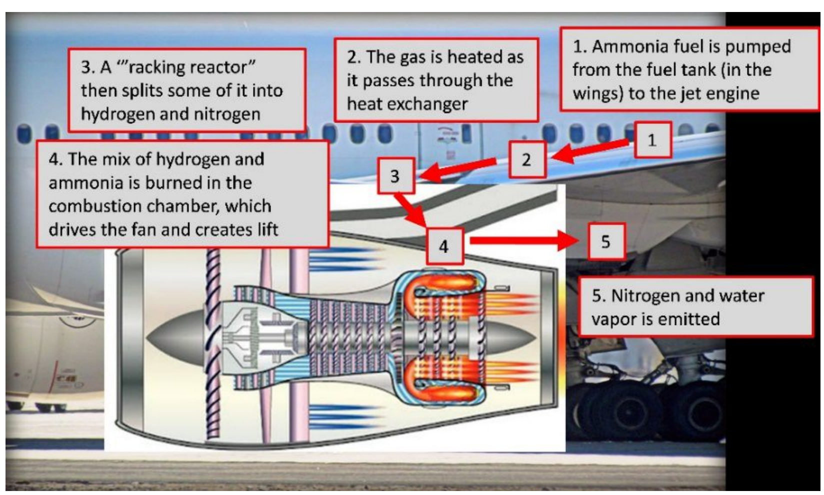
How Does Ammonia Propulsion Work?

Using ammonia as a fuel has already been a focus for the maritime and power generation sectors; however, it has only recently been proven to be a viable fuel for aviation propulsion systems. The "simplest" solution, which many are investigating, is using a single fuel tank and "cracking" some of the ammonia into hydrogen, then burning a mix of ammonia and hydrogen in the combustion chamber. The ammonia used in this solution needs to be anhydrous ammonia rather than the aqueous version used in cleaning products.

There are two potential ways that ammonia could be used for propulsion in aviation:

1. **Gas Turbines:** As shown in Figure 21 below, the ammonia will start as a liquid in the fuel tank, likely stored in the wing of the aircraft similar to how kerosene is currently stored. It will then be pumped for pressurization and sent to a heat exchanger, which warms it to a gas. The ammonia is then pumped to a "catalytic cracking reactor," which splits some of the gas into hydrogen and nitrogen. This mix of hydrogen, nitrogen, and ammonia is then moved to the combustion chamber in the jet engine, where hydrogen and ammonia are burned to drive the fan, create lift, and propel the plane. The by-product is water vapor, which is emitted out of the exhaust along with the nitrogen produced from cracking, i.e., no carbon emissions.

Figure 21. How Ammonia Propulsion in Jet Engines Could Work



Source: NASA, Citi Research

2. **Fuel Cells:** The two most promising fuels for fuel cells are hydrogen and ammonia. Until recently, the use of ammonia in fuel cells has been limited due to the tendency of ammonia to dissolve the cell membrane. Advances in solid oxide fuel cells (SOFC) and polymer electrolyte membrane fuel cells (PEMFC) are proving ammonia as a fuel for fuel cells can be a viable option.

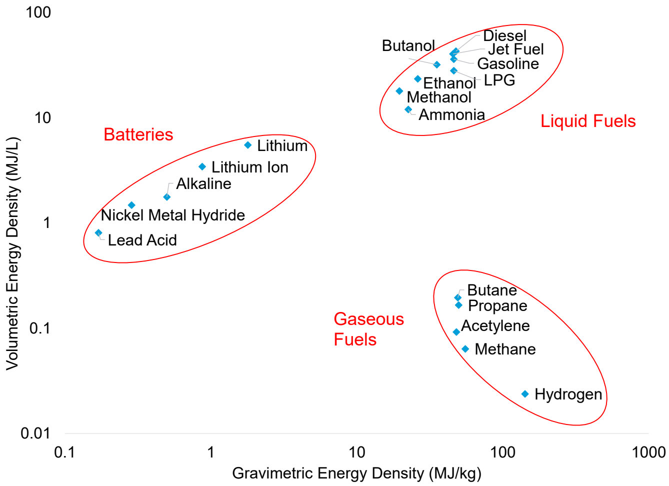
Key Benefits and Challenges of Ammonia Propulsion

There are some key benefits of using ammonia as a fuel for propulsion in aviation:

- **Retrofits are feasible:** Ammonia can be easily adapted from current engine technology and does not require a complete re-think of the current design of a civil aircraft. As a result, retrofits of existing aircraft engines are quite feasible.
- **Produced at scale:** Ammonia is already produced at enormous scale (although currently not very green) due to its high usage in agriculture (for fertilizer) around the world. It also has an existing, relatively global transport infrastructure system (however, this also may not be very green).
- **High energy density:** Ammonia has a high energy density (both volumetric and gravimetric) compared to other sustainable solutions, as shown in.
- **Safety is understood:** Ammonia is far less flammable than jet fuel and safety issues are better understood given its already wide usage.
- **Similar price to kerosene:** Ammonia currently trades at a similar price to kerosene, although producing green ammonia is more expensive. However, we believe that an increase in green ammonia volumes will drive economies of scale and drive its price more in-line with kerosene.
- **Carrier for hydrogen:** Ammonia can also be a used as an easier and cheaper "conduit" to transport hydrogen from large-scale production sites to large-scale generation sites (e.g., offshore wind), given that it can be converted into hydrogen via "cracking." The difficulties in storing and transporting hydrogen are discussed in more detail below. While there are alternative hydrogen carriers (e.g., Liquid Organic Hydrogen carriers), ammonia has zero carbon involvement, allowing it to be carbon free at both the source and at the end-use location.
- **Liquid at a relatively high temperature:** Ammonia needs to be stored at -33°C, which happens to be the temperature at cruising altitude. It does, however, need to be refrigerated on the ground (or a small quantity will have to be sacrificed as boil-off). This compares to hydrogen which needs to be stored at high pressure and at -253°C.

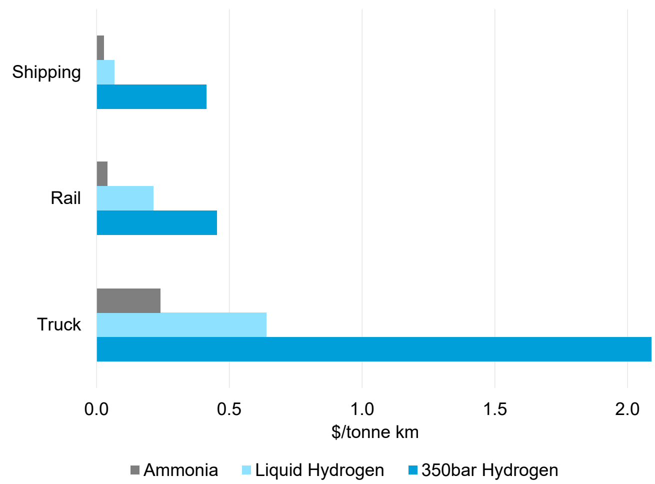
However, to be "truly" emission free, ammonia needs to be "green." Green ammonia is made by reacting nitrogen separated from air with hydrogen made by wind or solar-powered water electrolysis. The largest producers of ammonia today are the fertilizer companies that use steam methane reformer (SMR) hydrogen as feedstock, which is both energy and carbon intensive. These producers are currently in very early stages of exploring the production of green hydrogen.

Figure 22. Energy Densities of Various Fuels and Storage Media (log scale)



Source: Citi Research, Sjödin & Ekberg (2020)[13] Hydrogen – The future fuel for construction equipment Report

Figure 23. Cost of Transporting Hydrogen



Source: Citi Research, ACIL Allen Consulting report

The key setbacks/challenges of using ammonia for propulsion in aviation include:

- **It is heavy:** Ammonia is heavy in its liquid state. Although its energy density is better than other sustainable solutions, it is still less than kerosene. At -33°C ammonia has an energy density of 15.6 megajoules per kilogram (MJ/Kg) — 25% lighter than jet fuel — and a specific energy density of 15.6 MJ/Kg (less than 40% of jet fuel). This means that fuel tanks will need to be over 2x the size of those currently on a jet fuel aircraft, without taking into account the higher flammable point and slow flame speed, among other technical aspects.
- **It produces nitrogen oxide:** Although carbon emissions are a big focus, nitrogen oxide (NOx), which results in ozone layer depletion, is also produced via ammonia propulsion and needs to be reduced through filtration at the exhaust nozzle.
- **Hydrogen input costs:** Hydrogen is used as feedstock in the production of ammonia. The cost of renewable hydrogen (from solar/wind) is high given its high demand and low supply, but this will likely reduce with scale and increasing production efficiency.
- **Toxicity:** Ammonia is toxic and, as a result, strict procedures need to be in place to transport it. This is not new, however, as industries such as agriculture have implemented safe ammonia operating procedures for a long time.
- **Aviation safety and certification:** Research on increasing safety in civil aerospace has been relentless, with each new technology required to show it is at least as safe as its predecessor. Although ammonia is widely used and safety issues are well understood, there are still uncertainties with its use in aviation and additional concerns on handling its toxicity need to be addressed — for example, if there is a fuel leak or containment in a crash.

[13] Andreas Sjodin and Elias Ekberg, "Hydrogen – The Future Fuel for Construction Equipment", Mälardalen University Sweden, 2020

- **It may need dual fuel:** Given that ammonia propulsion in aviation is still in the development/R&D phase, it may require the use of dual fuel to initially be a viable solution. Until the technology catches up, a likely scenario would be to use kerosene to start the engine then switch to ammonia. This will likely be the preferred procedure by regulators given the lack of test flying hours.

Ammonia Is One of the Many Possible Solutions

There are several potential solutions being explored to either reduce or completely cut emissions in aviation. Most companies are investing in and exploring several different options that could emerge as the leading technology. We believe the future will likely be made up of different technologies to better address different markets and route lengths — for example, electric on short duration, and ammonia or sustainable aviation fuels on longer length flights.

The key benefits of ammonia when compared to other potential solutions for emission-free aviation include:

1. **All-Electric (short-haul solution):** Although all-electric would be the ideal solution, there are still significant constraints with battery technology as we highlighted in the Citi GPS report *Electric Aircraft: Flightpath of the Future of Air Travel*. We estimate that current battery energy densities limit a narrow body-sized aircraft to ~200 miles, while 2030 density forecasts would still only extend this to ~350 miles.

2. **Hydrogen (short/medium-haul solution):** Hydrogen has gained a lot of publicity recently; however, it needs to be stored in its deeply cryogenic liquid state (-253°ºC), which requires new infrastructure, major changes to aircraft configurations, and involves expensive transportation costs.

3. **Synthetic fuels and biofuels (long-haul solution):** Synthetic fuels and biofuels are currently not produced in anywhere near-enough volumes and still produce some emissions.

We believe that ammonia propulsion is a viable solution across all three types of routes: short/medium-haul for fuel-cell ammonia-propelled aircraft, and all distances from gas turbine ammonia-propelled aircraft.

Why Aviation Needs a Solution(s) for Emissions

In 2018, air travel was responsible for 2%-3% of global man-made carbon dioxide (CO_2) emissions, or 897 million tons according to the International Air Transport Association (IATA). If aviation was a country it would be the sixth largest source of emissions in the world.

Although efficiency is improving, the problem is that the amount of people who want to travel is growing faster than efficiency is improving. Assuming air traffic recovers back to pre-COVID-19 levels by the widely anticipated timeline of 2024 (in-line with IATA forecasts), and then continues its 4%-5% pre-pandemic annual growth through the mid-2030s, even if average CO_2 emissions per passenger kilometer continue to reduce at 1%-2% per year, we estimate total CO_2 emissions for aviation could triple by 2050. This could result in aviation's share of total CO_2 emissions increasing to 10%. Other factors affecting carbon emissions include:

– The longevity of aircraft, as a typical aircraft remains in service for 25 years on average, leading to very slow fleet turnover.

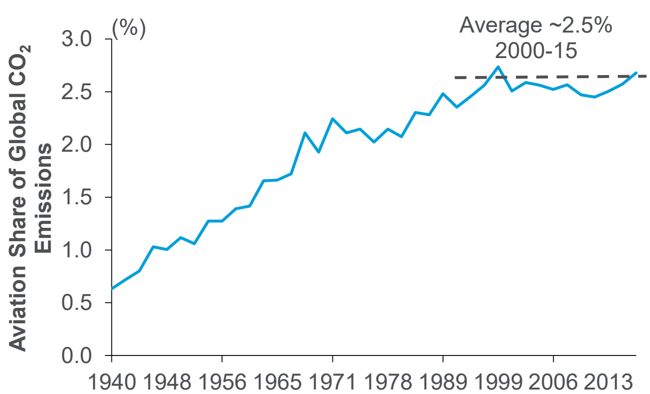
– The rate of reduction in fuel burn is likely to slow as gas turbine technology and the conventional tube-and-wings architecture of aircraft become increasingly mature.

– New regulations are forcing other industries to change, leveraging technology that may or may not already exist.

Public awareness and social pressure is increasing with a growing trend in "flight shaming" particularly prominent in Europe, where activists such as Greta Thunberg have publicized the Swedish term "Flygskam" — which literally translates in English to "flight shame."

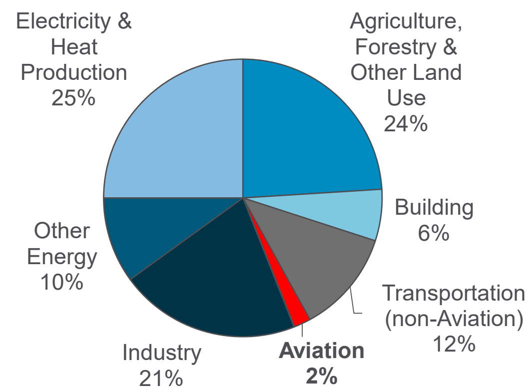
Aviation carbon emissions are very concentrated by region. The International Council on Clean Transportation estimates the top five countries for total passenger aviation-related carbon emissions are: (1) the U.S. (mainly domestic), (2) China, (3) the U.K., (4) Japan, and (5) Germany — while less developed countries, containing half of the world's population, accounted for only 10% of all emissions.

Figure 24. After Growing Steadily Through the 20th Century, the Aviation Share of Global CO2 Emissions have Stayed Flat at ~2.6% in the Last ~15 Years



Source: Citi GPS, *Electric Aircraft*

Figure 25. Aviation Makes Up a Small Proportion of CO_2 Emissions Relative to Other Industries – But This Could Grow to 10% by 2050



Source: Citi Research, IPCC (2014)

Several governments and global aviation authorities have already set emissions targets for aviation, including imposing fines and penalties on operators not meeting these targets. These include:

- Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) goals by the International Civil Aviation Organization (ICAO), where all international growth post 2020 has to be carbon neutral.
- The EU Emissions Trading System (EU ETS), where airlines operating in Europe (limited to intra-European Economic Area flights up to 2023) receive tradable allowances covering a certain level of emissions from their flights per year.
- EU Flightpath 2050, which targets cutting CO_2 emissions per passenger kilometer by 75%.

- Norway's announced target to make all domestic aviation fully electric by 2040. We believe that other countries will follow suit as technology — in particular battery energy densities — improves.
- Sweden's airline passenger tax, levied in 2018, of SEK 60 per passenger (~$7) on domestic routes and SEK 400 (~$45) on long-haul routes. Sweden expects this to help to reduce CO_2 emissions by 2% per year. Other airports could follow suit and add an additional carbon offsetting tax to the existing departure taxes.
- France's recent vote in favor of a bill to reduce carbon emissions that ends domestic air travel routes where the same journey could be made by train in under 2.5 hours. The bill still has to be voted in by the Senate before it can become a law. This was significantly less than the originally proposed four hours and we estimate it will only affect ~5% of domestic flights.

De-Polymerizing Plastics

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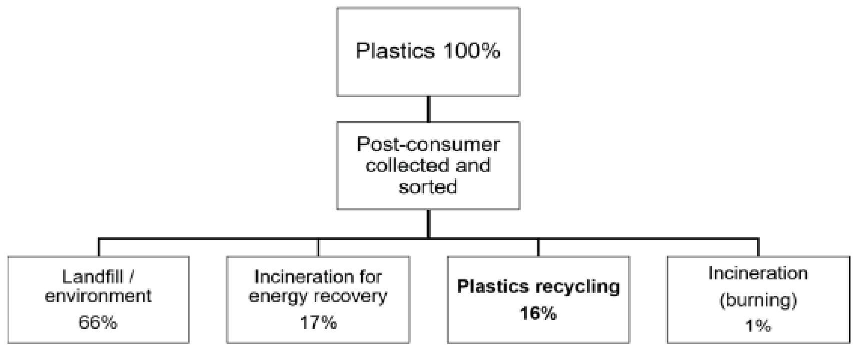
Advanced or chemical recycling — the class of processes to break apart polymer plastics into smaller reusable molecular building blocks — is seeing increased innovation and investment as it represents one of the final steps to close the loop for plastic materials. Most plastics recycling today is focused on mechanical recycling, where products are sorted through waste streams that are focused on the most homogenous and easy-to-recycle materials. Furthermore, collection rates for these plastics are low and the infrastructure and incentives to increase plastics recycling is sparse. Thus, chemical recycling has been advocated as the solution to close the loop on plastic materials and eliminate waste from landfills.

Figure 26. Plastics Recycling and Disposal, 2018



Source: Citi Research, IHS

The American Chemistry Council (ACC) called for a target of 30% recycled plastic in packaging by 2030, increasing to 40% by 2040. However, Independent Commodity Intelligence Services (ICIS) estimates that mechanical recycling can only reach a recycling rate of 16%. In 2020, only 16% of plastics were recycled in the U.S. with the rest disposed by incineration, exportation, or landfill. The development of the circular economy has accelerated as China imposed restrictions in 2018 on imports of plastic scrap and waste, causing imports to decline to 0.4 million metric tons (mmt) in 2019 compared to 10.7mmt in 2010. Plastics producers and consumer packaging companies are now partnering in an effort to expand commercial recycling capabilities and make inroads on the environmental component of their respective environmental, social, and governance (ESG) targets.

Mechanical recycling typically only processes polyethylene terephthalate (PET) and high-density polyethylene (HDPE), which are available in sufficient volume and identified by Resin Identification Code (RIC) 1 or 2. Plastics identified by RIC 3 to 7, however, are generally sent to landfills or incinerators. Other limitations of mechanical recycling include: (1) requirement of a clean waste stream, (2) finite recycling cycles due to degradation, and (3) recycled content can eventually end up in landfills due to downcycling of plastic to a lower quality or performance application.

Figure 27. Seven Types of Plastics

Label	Plastic type	Plastic name	Recyclable?	Sample uses
1 PETE	PET	polyethylene terephthalate	Recyclable	Water bottles, soft and fizzy drink bottles, pots, tubs, oven ready trays, jam jars
2 HDPE	HDPE	high-density polyethylene	Recyclable	Chemical drums, shampoo/conditioner bottles, bleach bottles, toys, household and kitchenware
3 V	PVC	polyvinyl chloride	Often recyclable	Window frames, drainage pipes, medical devices, flooring, car interiors, credit cards
4 LDPE	LDPE	low density polyethylene	Often recyclable	Squeezy bottles, toys, carrier bags, general packaging
5 PP	PP	polypropylene	Hard to recycle	Nappies, Tupperware, Margerine tubs, bottle caps, diposable cups and plates
6 PS	PS	polystyrene	Hard to recycle	Toys, rigid packaging, fridge trays, costume jewellery, disposable cutlery
7 OTHER	Other	other types of plastics	Hard to recycle	

Source: ASTM International Resin Identification Coding System

Advanced Recycling to Close the Loop

The biggest challenge facing the plastics recycling industry stems from the fundamental long-lasting nature of plastics — widely-used consumer plastic bags take 500 to 1,000 years to degrade. Mechanical recycling alone is not likely to solve this problem, as a number of plastics are not suitable and poor recycling infrastructure has led to low recycling rates. Ideally, advanced recycling technologies can take nearly all end-of-life materials and convert them into usable feedstocks and materials, eventually moving a meaningful share of plastic supply away from virgin, fossil fuel-based materials.

In addition to existing mechanical recycling, there are four leading advanced plastic recycling technologies:

4. **Depolymerization:** turns mono-material plastics (PET bottles) back into monomers (dimethyl terephthalate and ethylene glycol) by processes including methanolysis and hydrolysis. These monomers can be condensed and re-polymerized into PET, which has the same properties as virgin-grade PET.

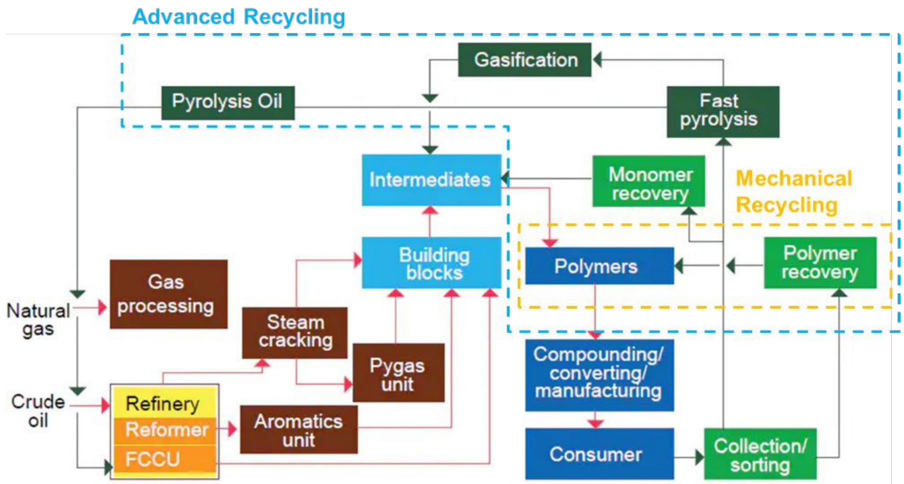
5. **Solvolysis (dissolution):** breaks down certain plastics into smaller parts with solvents that filter out impurities. The result is nearly equivalent to virgin polymers.

6. **Pyrolysis:** converts mixed plastic waste input into pyrolysis oil in an inert (oxygen-free) and high temperature (>500°C) atmosphere, which can be put into a cracker and further refined for new plastics production.

7. **Gasification:** converts mixed plastic waste into syngas (carbon monoxide and hydrogen) at high temperatures (>500°C), which is a building block for new chemicals. Gasification plants are generally expensive.

A host of advanced recycling technologies can convert plastics back into a variety of materials in the chemical value chain (Figure 28). However, mechanical recycling is limited to plastic-to-plastic recycling which often means downcycling.

Figure 28. Advanced Recycling in the Plastics Value Chain



Source: IHS Markit, Citi Research

Potential Barriers to Advanced Recycling

While advanced recycling seems like an obvious solution, we see several potential challenges that may slow or limit its disruptive power:

- **Economics of recycling:** Recycled material cannot yet compete with virgin plastics from a price and performance standpoint. Plastics companies with cost-advantaged feedstock positions likely cannot justify paying large premiums for recycled material that may not be equivalent to virgin materials. Outside of producers, the economics of collecting and sorting waste are unattractive. In order to overcome these economic challenges, advanced recycling will likely require government regulation and incentives, as well as a shift in the willingness of consumers to pay for recycled materials.

- **Criticisms of technology:** Many have argued that as a means of eliminating waste, chemical recycling cannot scale up quickly enough to address the growing problem of the world's dependence on plastics. Additionally, chemical recycling may not be as circular as claimed, with processes like pyrolysis creating their own GHG emissions. However, it is likely that the net benefits remain positive and initial investments are critical toward closing the loop in the future.

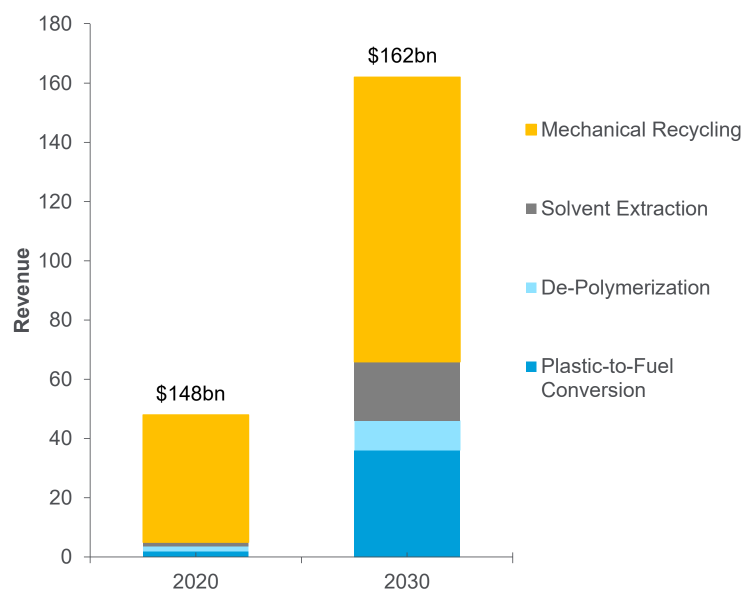
- **Shifting trends in plastics consumption:** The plastics industry, particularly nondurable plastics, has seen increasing criticism over the generation of waste, leading consumers, municipalities, and corporations to move away from plastics. Many will recall bans on plastic straws, plastic bag taxes, and a large shift toward aluminum cans on the back of public pressure. While consumers look for sustainable alternatives, plastics continue to capture a large majority of their demand and growth from other end-markets and emerging economies.

- **Alternative technology approaches:** Aside from substituting plastics, there are a number of approaches to re-inventing plastics. Bio-based plastics refer to a class of materials made from renewable feedstocks that come from plants or fermentation processes, intended to limit reliance on fossil fuels. Biodegradable plastics are also being developed to target the "forever" problem of plastic waste. While these technologies have some role to play, they are likely limited by scale and scope.

Big Investment, Partnerships, and Collective Action

As companies throughout the plastics supply chain put forth ambitious sustainability targets around net zero and waste, advanced recycling technology has become a focus of investment and innovation. The global recycling market is forecast to grow from $48 billion in 2020 to $162 billion in 2030 (Figure 29). The share of advanced recycling technologies is expected to grow from ~10% to ~40% from 2020 to 2030. Demand for sustainable plastics is being driven by both end-consumers and downstream brands. Large consumer brands have all made commitments to use more recycled materials in their products, including using a minimum of 25% post-consumer recycled plastics by 2025.

Figure 29. Polymer Recycling Technology Market



Source: IDTechEx, Citi Research

According to the American Chemistry Council (ACC), 64 projects in mechanical and advanced recycling have been launched in the U.S. in the last three years. Overall, these projects could remove more than 1mmt or 8.9 billion pounds of waste from landfills each year. A number of players are involved in the development of advanced recycling technology, from start-ups to large plastics producers. Furthermore, innovation has been encouraged by a number of governments, non-governmental organization (NGOs), and collective partnerships.

New Advanced Recycling Entrants Are Gaining Traction

There are a number of start-ups and new public companies tackling the recycling problem. Some are focused on creating virgin-like polypropylene resins using solvothermal extraction methods from consumer and industrial waste. Others take an approach around managing feedstock and collect a mix of plastic waste and sort it into an appropriate pyrolysis channel.

Recycling is a Major Focus Area for Global Plastics Producers

Global plastics producers have set targets for the collection, reuse, and recycling of plastic through their own actions and partnerships. To achieve their targets, the producers are investing in new technology including:

- **Advanced Recycling**
  - **Hydrothermal Plastic Recycling Solution (HydroPRS™):** employs supercritical water, heat, and pressure to convert plastic waste into chemicals and oils by breaking down the long-chain hydrocarbons and donating hydrogen to produce shorter-chain, stable hydrocarbon products for chemical feedstocks.
  - **Molecular Recycling:** uses mixed plastics to produce clean feedstock for new polymer production, including food packaging and healthcare items.
  - **Carbon Renewal Technology:** uses mixed plastic waste (except for PVC), which is then converted back to small molecules and building blocks to make new consumer products. This process reduces greenhouse gas (GHG) emissions by 20%-50% compared to traditional fossil fuel-based plastics production.
  - **Polyester Renewal Technology (PRT):** converts polyester plastics waste (bottles, carpet, and polyester-based clothing and carpet fibers) to monomers by glycolysis or methanolysis. These monomers can then by polymerized into new polymers. This process reduces GHG emissions by 20%-30% compared to traditional fossil fuel-based plastics production.
- **Mechanical Recycling**
  - Creates products with 40%-50% post-consumer material as well as low-density polyethylene made with 70% recycled plastic.
  - Sorts selection of polypropylene and polyethylene from the waste stream and further treats and color sorts it.
  - Offers polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) grades from renewables-based raw materials, including cooking and vegetable waste from food manufacturers.

Carbon Capture and the Alchemy of Air

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In the early 20th century, two Europeans gambled on taking nitrogen from the air to make artificial fertilizers.[14] **Fritz Haber and Carl Bosch bequeathed to the world the Haber-Bosch Process, which won them a Nobel prize, enabled the world to feed 9 billion rather than just 2 billion when natural fertilizers were falling short**…but also facilitated the use of gunpowder.

Stemming the rise in global temperatures today also requires a technological revolution to lower cumulative carbon dioxide levels in the atmosphere. Similar to taking nitrogen from the air to create fertilizers, the "alchemy of air" could offer a solution for removing carbon dioxide from the air and either sequestering it or finding new uses for it. The concept is rapidly becoming less far-fetched than it might seem, and is potentially mimicking one of the most important inventions of the last 120 years, proving that in theory the alchemy of air can work.

There is little doubt that carbon dioxide removal is a crucial tool in the climate mitigation toolbox. In the fight against climate change, the world needs to reduce its greenhouse gas (GHG) emissions massively to stop the rise of the concentration of atmospheric GHGs — particularly carbon dioxide. Well-recognized pathways include increasing the use of renewables in the power sector, switching road vehicles from internal combustion engines to electric vehicles, as well as carbon capture of concentrated CO_2 emissions in the flue gas of industrial facilities and storing/sequestering them in permanent geologic formations. However, another crucial approach is to remove atmospheric CO_2 from the air itself — whether through technological/engineered approaches like direct air capture (DAC), or through a whole range of nature-based solutions.

There are several broad types of carbon dioxide removal (CDR), which can be categorized in various ways. Here is one set of categories for grouping the many approaches:

1. **Nature-based solutions:** include afforestation/reforestation and improved forest management, restoration of coastal areas and wetlands ("blue carbon"), and soil carbon restoration.

2. **Enhanced natural processes, including hybrid natural/engineered solutions:** include land management to increase carbon content in soil through enhanced farming methods, bioengineered plants (e.g., Salk ideal plants), adding biochar to soils, carbon mineralization (enhanced/accelerated weathering), and oceanic options (iron fertilization and ocean alkalinization). This category could also include bioenergy with carbon capture and storage (BECCS), where biomass is burned for energy or processed for industrial production, with CO_2 emissions captured and stored geologically.

[14] See *The Alchemy of Air: A Jewish Genius, a Doomed Tycoon, and the Scientific Discovery That Fed the World but Fueled the Rise of Hitler,* by Tomas Hager.

3. **Purely technological solutions, notably direct air capture (DAC):** building machines that capture CO_2 out of the atmosphere through the new "alchemy of air." This category could also include electrochemical separation of CO_2 from seawater.

Direct Air Capture and Other Engineered Solutions

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Once viewed as a method to ease the environmental burden of fossil fuels, and extend their use as baseload fuels, carbon capture, utilization, and sequestration (CCUS) is now being seen as a critical component of an "all of the above" climate strategy. We believe the next wave of excitement could be focused on the most challenging end of the CCUS spectrum — pulling carbon directly from the air.

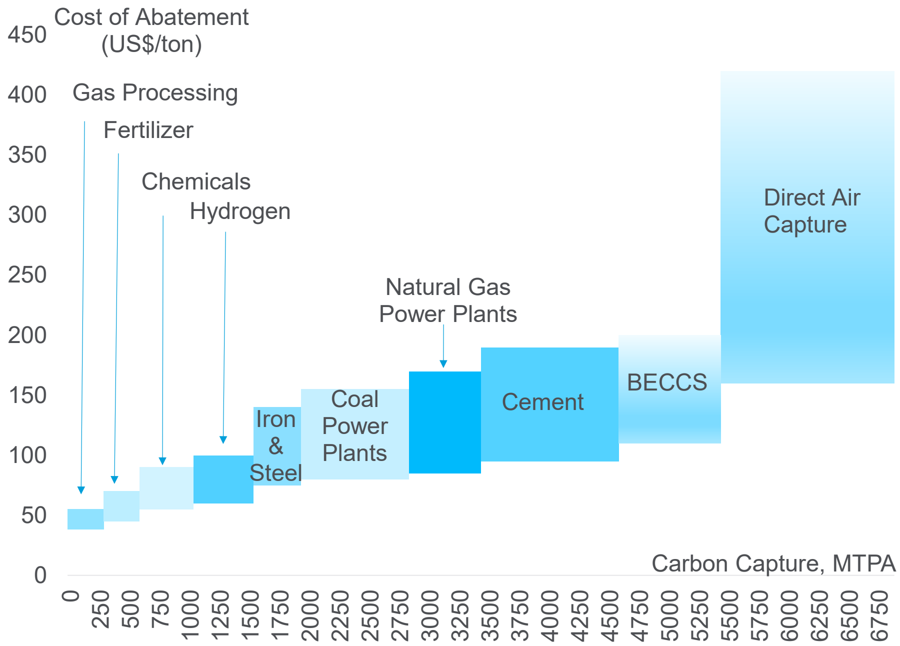
Direct air capture (DAC) is almost certainly likely to stay at the high end of the carbon capture cost curve for the foreseeable future, given the much lower concentration of CO_2 in ambient air versus much higher concentration in industrial and power generation flue streams. However, developments are under way to bring down its cost and we believe it will also garner focused political support. This reflects the ability of DAC to accelerate the pace of emissions reductions and also offset the risks associated with other carbon reduction pathways.

Thus, despite the relatively higher cost versus point source capture, directed policy support should occur, with DAC as a "backstop" within a climate strategy framework, and even if modest in capacity, could lead to the development of a new sub-industry.

So how does direct air capture work? The two most advanced capture methodologies utilize either liquid solvents or solid sorbent filters. In the approach utilizing a liquid solvent, air is pulled into a contactor system, which looks like a cooling tower with a series of giant fans. Inside the contactor, air passes over structured packing to increase surface contact with a strong basic hydroxide solution such as potassium hydroxide. CO_2 binds with the solution, removing the molecules from the air and trapping them as carbonate salts. This is followed by a chemical process, which results in precipitated calcium carbonate pellets. The pellets are then heated in order to release a pure stream of CO_2, while the used pellets are recycled and reused.

In the filter approach, air is drawn into a collector via fans and then passes through a solid sorbent filter. Several types of porous materials could be used including mesoporous silicas, zeolites, activated carbon, carbon nanotubes, porous organic polymers, or metal-organic frameworks. Sensors indicate when the filters are full at which point the collector is closed and air intake ceases. The collector is then heated to release the CO_2 creating a high purity stream. At present, the load factor (related to surface area of contact) as well as heat and water requirements appear to favor filters but research on the chemistry and materials utilized continues to progress.

Figure 30. Global Carbon Capture Abatement Cost Curve (Including $20/t for Transport and Storage Costs)



Source: Citi Research

At the start of 2021, there were 15 small DAC facilities in operation capturing more than 9,000 tons of CO_2 per year. Cheap power and efficiencies that accompany commercial-scale development appear required to make DAC competitive on the CCUS cost curve. That said, advancements could potentially tighten the cost range towards the low end, and eventually push the low end down. Options like using cheap renewable power or utilizing reactive rock formations could be also used to lower cost.

What does potential lower cost mean for the long-term future of DAC? It depends for now on the market structure within which the captured carbon is priced. Emissions trading systems in Europe currently incentivize the development of carbon capture for the low end of the CCUS curve, but as EU emission caps fall over time, allowance prices should rise, corresponding to a higher marginal cost of carbon abatement. This would make DAC more competitive with the cost of abatement in the most challenging sectors. In the U.S., DAC is currently being incented through the 45Q tax credit and the California Low Carbon Fuel Standard (LCFS) system. Another pathway to pay for DAC is through the sale of carbon offsets where companies offset their emissions by paying DAC facility operators directly to capture CO_2. This is currently an embryonic market and cannot be relied upon for a majority of project revenues.

We believe a carve-out for DAC under something like the U.S. federal tax credit is the proper approach at present as this technology can act as an important part of a broader climate change policy. DAC would be promoted alongside other emissions reduction pathways in order to establish the sub-industry, which would reduce the risks along the path to net zero and accelerate the timing of the achievement of climate coals.

How big could DAC become assuming economics and policy support improves? In the International Energy Agency's (IEA's) Sustainable Development Scenario, DAC is capturing 11 $MTCO_2$/year in 2030, ramping to 117 $MtCO_2$/year in 2050, and rising further to 741 $MtCO_2$/year — or 7.1% of all carbon captured — in 2070. The investment to reach the 2070 capture rate in the IEA's scenario is ~$600 billion under current technology. If fully funded by governments, incremental government spending of $12 billion annually on facility expansion around the globe looks manageable and costs should decline. If the U.S. were to fund a third of the spending, it would only account for 0.2% of federal spending.

Supercharging the Carbon Cycle: Soil Carbon Sequestration and Other Nature-Based Solutions

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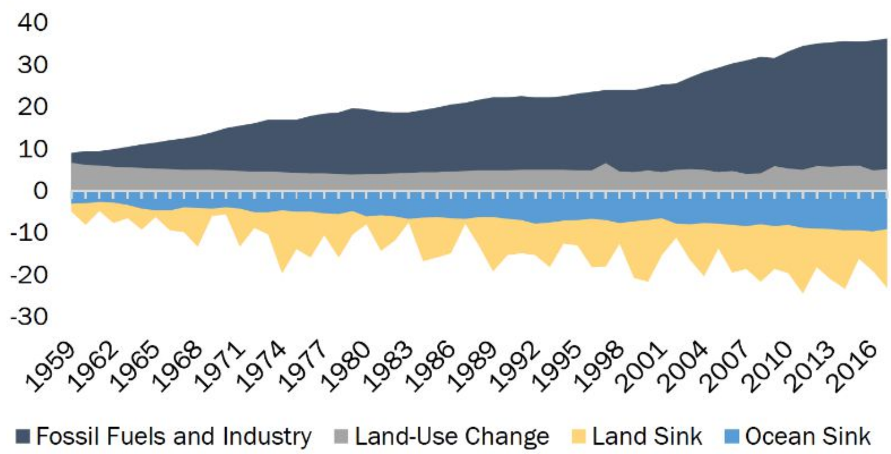
Outside of human-made GHG emissions into the atmosphere from fossil fuels, industrial production, agriculture, and land-use change, the world is "breathing in and out" CO_2 in the form of the "carbon cycle." This includes terrestrial and ocean sinks where the gross intake of CO_2 is greater than the gross output of CO_2. Despite being complex, there are ways to enhance these carbon sinks, which would be a big boost towards getting to net zero by mid-century and net negative GHG emissions in the second half of the century.

Figure 31. Global Emissions Sources, Sinks, and Net Atmospheric Accumulation ($GtCO_2$, 1959-2017)



Source: EFI, Global Carbon Project

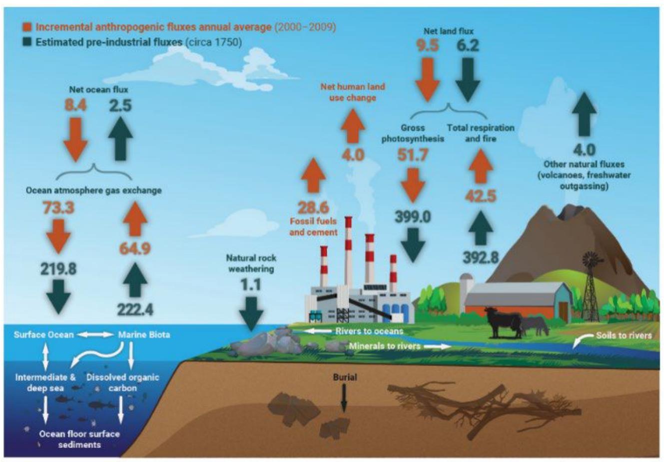
Enhancing land-based carbon sinks means storing more carbon in the terrestrial biosphere.[15] This includes land use and management practices in forests and agricultural land. Plants cycle carbon on a short-term basis, but the main focus for enhancing carbon sinks is on longer-term carbon stocks, with CO_2 as accumulated and persisting in woody biomass, debris, and soil organic matter. For plants, this means growing more biomass per unit of land, maintaining this for a longer period of time, and/or reducing the rate of release of CO_2 from that biomass that can happen, say due to fire.

[15] Enhancing carbon sinks is a wide-ranging topic. For more, see: The National Academies of Sciences, Engineering, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, 2019; and Energy Futures Initiative, *From the Ground Up: Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal,* December 2020.

For soil organic carbon, this would mean increasing the rate of input of plant detritus into the soil, and/or reducing the rate of decomposition of organic compounds that release CO_2. Agricultural management methods for cropland and grassland include reduced tillage or planting of cover crops that increase organic carbon in the soil.

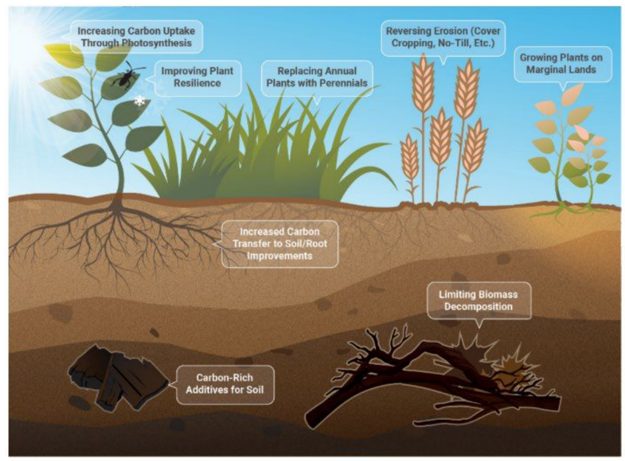
One exciting area of research has been bioengineering crops to grow deeper roots that store more carbon in the soil. This bioengineering could range from targeted breeding and plant selection, to genetic modification and gene-editing. The U.S. agency ARPA-E as well as the independent Salk Institute are both pursuing these kinds of efforts.

Figure 32. Schematic of the Global Carbon Cycle



Source: EFI

Figure 33. Biological and Terrestrial CDR Pathways



Source: EFI

The Salk Institute's Harnessing Plants Initiative (HPI) is focusing on developing "Salk ideal plants," modifying key agricultural crops (corn, soybeans, wheat, rice, cotton, and canola) to have deeper roots that feature more suberin, a plant material that could act as long-lasting carbon storage. Such plants could also promise higher yields and improve soil health.[16]

Meanwhile, the ARPA-E ROOTS program "[seeks] to develop advanced technologies and crop cultivars that enable a 50% increase in soil carbon accumulation while reducing N_2O emissions by 50% and increasing water productivity by 25%.[17] Advanced root systems that increase soil organic matter can improve soil structure, fertilizer use efficiency, water productivity, crop yield, climate resilience, and mitigate topsoil erosion — all of which provide near-term and sustained economic value.

[16] Salk Institute, Harnessing Plants Initiative, *Harnessing Plants, Saving the Planet,* PDF file, 2017.

[17] "Rhizosphere Observations Optimizing Terrestrial Sequestration," ARPA-E, accessed October 8, 2021.

Figure 34. Conventional Agricultural Management Actions to Increase Organic Carbon Storage

Management Practice	Increased Carbon Inputs	Reduced Carbon Losses
Increased productivity and residue retention	X	
Cover crops	X	
No-tillage and other conservation tillage	X	X
Manure and compost addition	X	
Conversion to perennial grasses and legumes	X	X
Agroforestry	X	X
Rewetting organic (i.e., peat and muck) soils		X
Improved grazing land management	X	X

Source: National Academies of Science, Engineering, and Medicine

The whole range of nature-based solutions for CDR requires improved policy frameworks that include economic incentives, to imbue land use decision-making with carbon removal in mind. There is now a fairly well-developed voluntary carbon market for carbon offsets related to forestry projects. However, such markets are not yet in place that, for instance, value soil carbon, or other CDR considerations related to land use or agriculture. And while voluntary carbon markets might be helpful for a while, these incentives could eventually be incorporated into wider compliance carbon markets over time. Unlocking the full potential of CDR through enhancing terrestrial carbon sinks likely requires enabling policy and carbon prices.

The Disruptive Potential of Voluntary Carbon Markets, with a Focus on Forestry

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Within a thorough legal framework and through innovative investment schemes or vehicles, afforestation and reforestation projects are among the largest potential nature-based carbon abatement solutions, by volume of emissions mitigated. Afforestation and reforestation investments can rely on renewable energy sources, provide support for local communities, operate on a scale large enough to significantly improve the natural environment and preserve wildlife, while also offering attractive investment returns. All in all, natural solutions are among the most cost-effective pathways on a dollar per ton of CO_2 equivalent ($/t$CO_2$e) basis. Outside of hybrid natural/engineered solutions, these natural carbon sinks can be boosted by smart agriculture, enhanced sequestration in soils and crop roots ("carbon farming") as discussed earlier, forestry management, coastal and wetland management ("blue carbon"), and other land-use sectors.

Afforestation and reforestation investments are *carbon removal* solutions, which rely on the natural absorption of carbon from forest ecosystems and plant material to offset current emissions and even draw down accumulated emissions from prior years, creating the possibility of a net removal or "net negative emissions." This is not only important for offsetting remaining gross positive emissions, but also to remove historic emissions and reduce atmospheric carbon dioxide levels further, as part of "climate restoration."

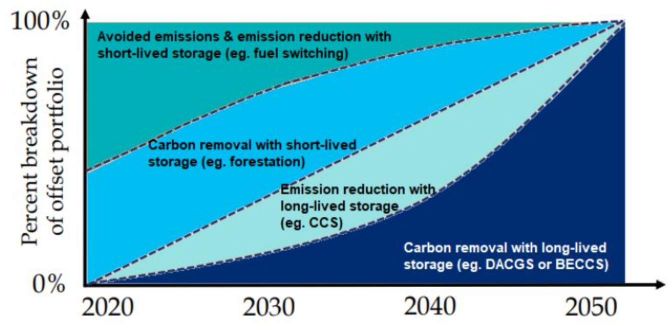
Yet, afforestation and reforestation projects can also run into issues, which must be addressed in order for investment to function well. In particular, carbon storage in forests may not be entirely secure, with the risk of release by decay, forest fires over time, or at a later stage in case of conversion into firewood. Further, the scale of forestry solutions does face land area constraints and issues of competing use of the land for food.

Figure 35. Estimated Cost and Scale of CDR Pathways for Net-Negative Emissions

Pathways	Cost at Scale ($/Mt$CO_2$)	Removal Rate (GtCO_2/yr)	Removal Capacity (GtCO_2/yr)
Forestry	$15-$50	U.S.: 0.25 to 0.60 Global: 2.5 to 9.0	U.S.: 15 to 38 Global: 1.125 to
Agricultural Soil Management	$0-$5	U.S.: 0.25 Global: 3	U.S.: 7 Global : 90
Bioenergy with carbon capture and sequestration (BECCS)	$70 electricity, $37-$132 fuels	U.S.: 0.5 to 1.5 Global: 3.5 to 15	
Carbon Mineralization: Surficial existing tailing	$10-$20	U.S.: 0.001 Global: 0.02 to 0.2	U.S.: 1 Global: 10
Carbon Mineralization: Surficial mining and grinding	$50-$500	Unknown	Unlimited
Carbon Mineralization: Produce alkaline water from calcite	<$10		
Carbon Mineralization: In-situ basalt and peridotite	$20-$5,000	Unknown	Unlimited
Coastal (Blue Carbon)	<$10	U.S.: 0.024 to 0.05 Global: 0.13 to 0.8	U.S.: 0.26 to 4 Global: 8 to 65
Direct Air Capture (DAC)	$90-600	Large	

Source: EFI, National Academies of Sciences, Engineering, and Medicine, Citi Research

Figure 36. Technology Contributions to Net Zero Over Time



Source: The Oxford Principles for Net Zero Aligned Carbon Offsetting, Citi Research

The most direct method for financially benefiting from carbon removal strategies through afforestation and reforestation projects is via the carbon credit market. Carbon crediting is the process of issuing verified carbon reduction units to projects ensuring avoided or sequestered emissions. To be clear, forestry investments are just one option as carbon credits can be awarded for any compliant offsetting project, including DAC as noted earlier.

Forest carbon finance requires patient capital due to large upfront capital requirements and longer time horizons of cash flows — it may take no less than five years before projects begin generating income in the form of carbon credits. The carbon removal potential of the investment, and therefore the primary source of income, is specific to each forestry investment. For similar amounts of financing, afforestation or reforestation investments may result in greater carbon removal in the medium-to-long term relative to other forestry practices in one area while being less effective in others. This difference depends on the arboreal species being planted, their growth rates, favorable weather conditions, and the cost of labor or the cost of preservation of the land from deterioration, including flooding and fire insurance costs.

These setbacks can be mitigated through direct revenue creation linked to land usage in the early years of a Reduce Emissions from Development and Forest Degradation (REDD+) project when the project does not yet generate revenue from carbon sequestration, as young trees only have a fraction of the carbon capacity of older trees. Ways to enhance the cash flows of the investment include eco-tourism, hunting or fishing leases, other public finance programs for land and water conservation, agroforestry, and selective timber harvesting.

Under the right conditions, the demand for offsets, including from forestry, may increase dramatically over the next decade. The Taskforce on Scaling Voluntary Carbon Markets (TSVCM) estimates the voluntary carbon offset market may grow up to 15-fold by 2030, lifting also demand — and hence prices — from forestry-based solutions.

Despite the great progress made in finding legitimate ways to facilitate reforestation, the area remains controversial for reasons related to science, potential greenwashing, and externalities. When it comes to science the main issues relate to design, and in particular to assure an enhancement rather than destruction of biodiversity, and the appropriate selection of trees and other plants to make sure the new forests can maximize capture and retention of emissions.[18] Greenwashing problems typically accompany efforts by timber companies to foster reforestation as a mechanism to facilitate continued lumbering. Negative externalities include problems of maintenance such as forest fires, litter and other issues related to ecotourism. There are also impacts on local factors, including potentially reduced space for housing, industry and farming; increased local poverty; reduced critical infrastructure space; and increased property taxes.

New Scientific Developments Beyond DAC

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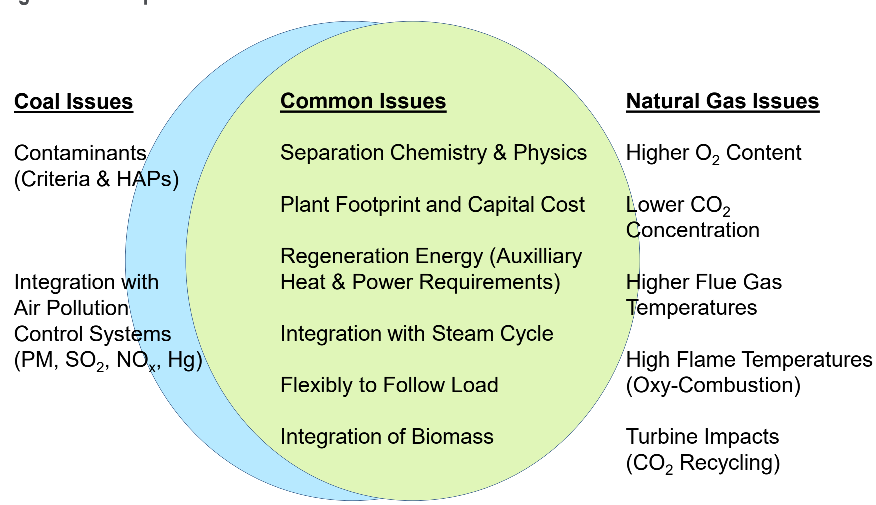
It is no accident that a significant amount of research and development emerged alongside the U.S. shale revolution. Indeed the discovery, globally, of abundant and low-cost natural gas has turned environmentalists' as well as fossil fuel producers' attention to the use of natural gas in power generation as a transition fuel for a cleaner electricity future. There is a growing consensus that a combination of renewable fuels development and battery technological progress will not be able to substitute adequately for gas-fired power plants in the near term. Gas-fired power generation, with CCUS and a greater blending of renewable natural gas and hydrogen into feedstock, can make for low-carbon peaking power that complements renewables.

There are considerably more costly and difficult conditions surrounding CCS for natural gas combined cycle (NGCC) power plants than there are for coal-fired plants. The advantage of NGCC plants is that they produce about half of the carbon emission per kilowatt hour (kWh) than coal; however, the problem is that the lower concentration combined with the accelerating growth of NGCC plants as coal plants are retired, increases the cost of decarbonizing them.

Figure 37. Comparison of Coal and Natural Gas CCS Issues



Source: U.S. Department of Energy

[18] See S&P Global Market Intelligence, "Scientists See Problems with Some Carbon-Offsetting Tree Planting Programs," June 23, 2020 and its review of scientific literature on these subjects.

The U.S. National Carbon Capture Center has been announcing new achievements on the road to reducing the costs of CCS for natural gas plants, but from a theoretical basis it would appear the use of solid oxide fuel cells (SOFC) might warrant more R&D in offering an economically-appealing approach. SOFC is being touted as the way forward and R&D is focusing on ways to decrease costs through economies of scale, increasing its useful lifetime, decreasing its currently required high temperatures, and enhancing its retrofit-ability for existing power plants. Like so many other emerging and disruptive technologies, the big hope is that the economies of scale will improve the accessibility and economics of emerging technologies.

While NGCC+CCS may have higher costs than coal+CCS on a per tCO_2 basis, policymakers in Europe and North American are largely ruling out coal in the future energy mix. Given this, NGCC+CCS is still expected to see falling costs, and with post-combustion carbon capture costs in the $70-$80/t range, could be “in the money” in the near future as long as CCS is eligible for relevant carbon prices, and if these carbon prices are high enough (alone or in combination). Meanwhile, in emerging markets, notably China and India, policymakers may yet explore coal+CCS further. In all cases, R&D and deployment should drive economies of scale and “learning by doing” to drive down costs and reduce emissions in the power sector, as part of a portfolio of climate mitigation approaches.

mRNA Vaccines

A New Frontier in Vaccine R&D

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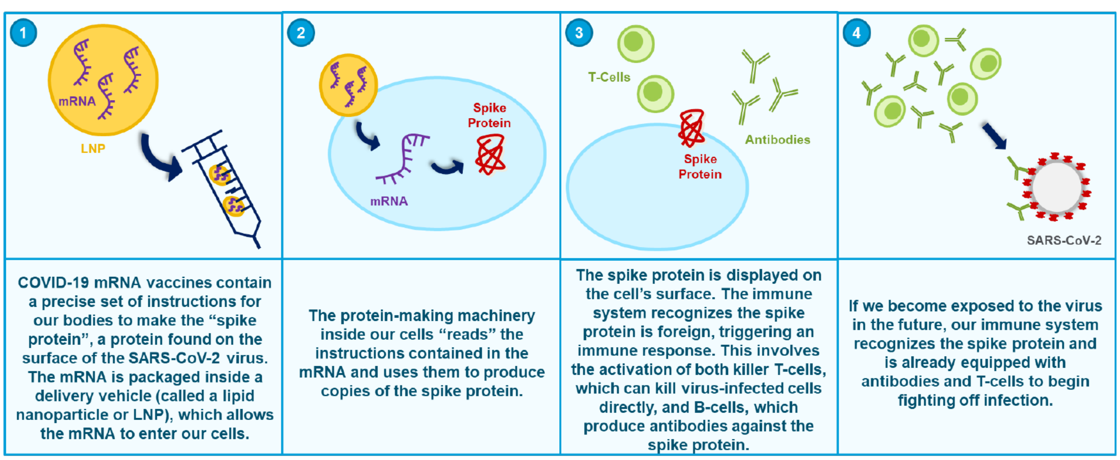
Just last year, messenger RNA (mRNA) was still considered a largely unproven technology platform despite decades of scientific research aimed at unlocking its therapeutic potential. Fast forward to today, and mRNA vaccines have become one of our most powerful weapons against COVID-19. Based on data from the Centers for Disease Control and Prevention (CDC), over 395 million doses of mRNA vaccines have been administered in the U.S. alone and over 185 million Americans have been fully vaccinated with one of the two authorized mRNA vaccines.[19] While it is still relatively early days for the technology, with the rapid success of mRNA vaccines for COVID-19, the broader potential of mRNA platforms cannot be ignored. Clinical trials are already underway testing mRNA vaccines for influenza (flu), Zika, cytomegalovirus (CMV), rabies, and other infectious diseases. In addition, researchers are leveraging mRNA as a potential therapeutic tool to treat genetic diseases, autoimmune disorders, and even cancer.

How mRNA Vaccines Work

The basic idea behind mRNA vaccines and therapeutics is relatively simple. mRNA essentially serves as an instruction manual that our cells use to make proteins. mRNA medicines are designed to exploit this natural biological process. In theory, scientists can design mRNA strands that are programmed with the precise instructions for building any protein of their choosing; for example, a healthy copy of protein that is defective in a certain genetic disease or an antigen found on the surface of a virus. For COVID-19 vaccines, the mRNA contains the instructions for building the so-called "spike protein" found on the surface of the SARS-CoV-2 virus. Like other types of vaccines, the goal is to mimic a natural infection with the virus to train our immune system to recognize and fight off the virus if we become exposed to it in the future. Conventional vaccines accomplish this by introducing an inactivated, weakened, or modified portion of the virus itself, whereas mRNA leverages the body's own protein making-machinery to produce a protein found on the virus.

Figure 38. How COVID-19 mRNA Vaccines Work



Source: Citi Research; John Teijaro and Donna L. Farber, "COVID-19 Vaccines: Modes of Immune Activation and Future Challenges,".. *Nature Reviews Immunology.* 21(4):195–7, 2021.

[19] "COVID Data Tracker," Centers for Disease Control and Prevention, data as of October 6, 2021.

Decades in the Making

COVID-19 vaccines have served as rapid proof-of-concept for mRNA vaccines as a class, as we now know mRNA can produce highly effective and safe vaccines. Although these vaccines were developed, tested, and authorized all in less than 12 months, the foundational mRNA technology is a product of over 30 years of research. Recent scientific advancements have overcome historical challenges with creating mRNA medicines. These include efforts to: (1) improve the stability of the mRNA, as mRNA is an inherently unstable molecule; (2) prevent an immune reaction to the "foreign" mRNA when it enters the body; (3) facilitate safe and effective delivery of the mRNA to the target cells/tissues; and (4) ensure the mRNA yields a sufficient amount of protein to have the intended therapeutic effect.[20]

The Advantages of mRNA

- **Speed:** A defining advantage of mRNA vaccines is their rapid pace of development. Prior to the pandemic, leading mRNA companies had already laid the groundwork by refining processes for synthesizing and delivering mRNA. Therefore, once the genetic sequence of the SARS-CoV-2 virus became known in January 2020, scientists were able to rapidly begin creating mRNA vaccines against the virus. Moderna's vaccine was designed in just two days and the first batch was produced 25 days later.

- **Flexibility:** mRNA platforms are readily adaptable, making mRNA vaccines well-suited for a rapidly evolving virus. As a virus mutates, the vaccine can be updated simply by tweaking the mRNA sequence to target the new strains of the virus. While data suggests both authorized mRNA vaccines for COVID-19 (which are based on the original SARS-CoV-2 sequence identified in Wuhan) are effective against known variants, clinical trials have proactively begun testing new vaccine candidates specifically targeting the Beta and Delta variants.

- **Manufacturing efficiency:** The manufacturing infrastructure for mRNA vaccines is highly versatile and generally requires a smaller footprint compared to traditional egg-based or cell-based vaccine manufacturing (these methods involve growing the virus in chicken eggs or animal cells, respectively). With mRNA, once manufacturing processes are in place vaccine production can be scaled relatively quickly (see Figure 39). Additionally, the same facilities/processes used to produce one mRNA vaccine can be swiftly adapted to manufacture an mRNA vaccine containing a different sequence, again making mRNA vaccines a promising strategy for addressing a rapidly evolving virus.

Figure 39. COVID-19 Vaccine Revenue Guidance for mRNA Vaccines

	1Q 2021A Revenues	2Q 2021A Revenues	2021 Guidance		2022 Guidance
			Revenues	Global Mfg. Capacity	Global Mfg. Capacity
Moderna	$1.7 billion	$4.2 billion	**~$20 billion**	800 million to 1 billion doses	2 billion to 3 billion doses
Pfizer / BioNTech *	$3.5 billion	$7.8 billion	**~$33.5 billion**	3 billion doses	4 billion doses

* Pfizer and BioNTech have a global 50/50 profit share arrangement. Under the arrangement, Pfizer books full revenues for all territories outside of Germany, Turkey, and China and BioNTech's share of gross profits are booked in cost of sales. 1Q 2021A and 2Q 2021A figures in the table reflect revenues reported by Pfizer. Pfizer and BioNTech have guided to global revenues of ~$33.5B for their vaccine based on supply agreements in place.

Source: Citi Research, Company Reports

[20] Norbert Pardi et al., "mRNA Vaccines — A New Era in Vaccinology," *Nature Reviews Drug Discovery* 17 (April 2018): 261–279.

COVID-19 Vaccines Could Be Just the Tip of the Iceberg for mRNA Technology

Beyond COVID-19 vaccines, clinical trials are currently underway evaluating mRNA vaccines for a number of other infectious diseases including influenza, Zika, rabies, HIV, and others (Figure 40). The most advanced of these programs include a Zika vaccine and a cytomegalovirus (CMV) vaccine, both in Phase 2 development. There is also a rich pipeline of mRNA vaccines in preclinical testing with additional vaccines expected to advance into clinical trials over the next ~12 months.

Figure 40. Clinical Trials for mRNA Vaccines Against Diseases Other than COVID-19

Disease	Vaccine Name	Development Stage
Influenza	mRNA-1010	Phase 1/2
	SP0273	Phase 1
Zika	mRNA-1893	Phase 2
CMV	mRNA-1647	Phase 2
RSV	mRNA-1345	Phase 1
Rabies	CV7202	Phase 1
	GSK3903133A	Phase 1
hMPV/PIV3	mRNA-1653	Phase 1
HIV	mRNA-1644	Phase 1

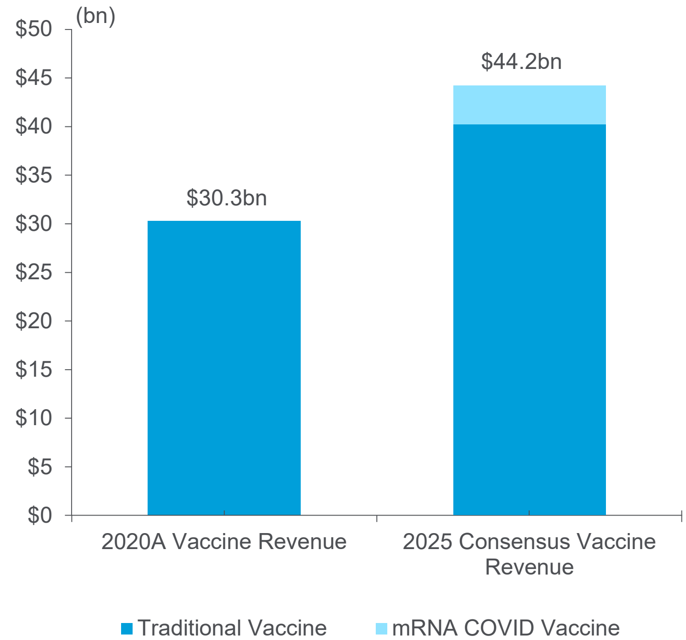
Abbreviations: CMV: Cytomegalovirus, RSV: Respiratory Syncytial Virus, hMPV: Human Metapneumovirus, PIV3: Parainfluenza Virus Type 3, HIV: Human Immunodeficiency Virus

Source: Citi Research, clinicaltrials.gov

mRNA Vaccines Could Disrupt the ~$30 Billion and Growing Global Vaccine Market

Prior to COVID-19, the global vaccine market had been dominated by four players. Together, these four companies generated ~$30 billion in global vaccine revenues in 2020. Based on consensus estimates this figure is expected to grow to ~$44 billion by 2025 (Figure 41) and could increase significantly more if annual COVID-19 boosters become a reality and/or if additional pipeline programs come to fruition. Although manufacturers of traditional vaccines (for example, live-attenuated, inactivated, or recombinant vaccines) are at risk of disruption from mRNA, it is worth noting that three of the four leading vaccine players have made recent investments in mRNA technology.

Figure 41. Total Vaccine Sales for the Four Largest Global Vaccine Players Are Expected to Grow from ~$30 Billion in 2020 to ~$44 Billion in 2025



Note: Consensus vaccine revenue estimates for three of the largest companies do not break out potential COVID-19 vaccine revenue.

Source: Citi Research, VisibleAlpha, Company Reports

mRNA Flu Shots Could Be Next

We estimate the seasonal flu vaccine market is a ~$5 billion to $6 billion annual opportunity (measured by 2020 revenues from the four dominant players in the market). Given production timelines for conventional flu shots, the target strains are typically selected at least six months in advance based on researchers' predictions on which strains of the virus are most likely to be circulating during the coming flu season.[21] mRNA vaccines appear particular well-suited to break into the seasonal flu market. The condensed development timelines could allow mRNA vaccine manufacturers to select vaccine strains closer to the onset of the actual flu season. This should reduce the risk of a mismatch between the vaccine strains and the dominant circulating strains during flu season as the virus changes, potentially resulting in a more effective vaccine. Based on data from the CDC, over the 2009 to 2020 time period the effectiveness of the flu shot in the U.S. ranged from 19% (2014-15 season) to 60% (2010-11 season), suggesting clear room for improvement.[22] Two mRNA flu vaccines are already in clinical trials with at least three more programs at the discovery stage. One vaccine candidate is also advancing a vaccine candidate that combines the company's COVID-19 and flu vaccines into a single-shot.

[21] "Selecting Viruses for the Seasonal Influenza Vaccine," Centers for Disease Control and Prevention, August 31, 2021.

[22] "Effectiveness of Seasonal Flu Vaccines from the 2009-2021 Flu Seasons," Centers for Disease Control and Prevention, August 26, 2021.

Remaining Questions & Potential Barriers to Adoption

Despite the promise and recent success of mRNA platforms, there are still challenges to overcome. For one, while mRNA vaccines for COVID-19 have proven highly effective, there are disease-specific factors that will need to be overcome as mRNA vaccines expand into other infectious diseases, especially in areas where conventional vaccine technologies have thus far failed to produce an effective vaccine (e.g., HIV). Second, the field remains in its early days and more data is needed to better understand the durability of protection afforded by mRNA vaccines and long-term safety. Third, there are logistical challenges. Given the inherent instability of mRNA, mRNA vaccines have stringent storage requirements creating practical challenges for global vaccine distribution. The authorized mRNA vaccines must be shipped in ultra-cold temperature containers (-90°C to -60°C or -130°F to -76°F for the Pfizer/BioNTech vaccine, and a less stringent -50°C to -15°C or -58°F to 5°F for the Moderna vaccine) and can remain stable for up to one month in the refrigerator.[23]

During the pandemic, viral vector vaccines, specifically adenovirus vaccines (e.g., those developed by J&J and AstraZeneca/Oxford), have also been developed at record speed. Viral vector COVID-19 vaccines have faced their own set of challenges (e.g., lower headline efficacy numbers, manufacturing issues, rare cases of blood clotting events); however, a notable advantage they have over mRNA vaccines is their stability. That being said, work is underway to loosen the cold-chain storage requirements of mRNA vaccines. This includes efforts to develop refrigerator-stable vaccines and lyophilized (freeze-dried) formulations.

[23] "Pfizer-BioNTech COVID-19 Vaccine Storage and Handling Summary," Centers for Disease Control and Prevention, PDF file, August 24, 2021; "Moderna COVID-19 Vaccine Storage and Handling Summary," Centers for Disease Control and Prevention, PDF file, August 24, 2021.

Meet Me at the Metaverse Mall

Realistic Virtual Venues Are Changing the Way We Socialize, Shop, and Spend

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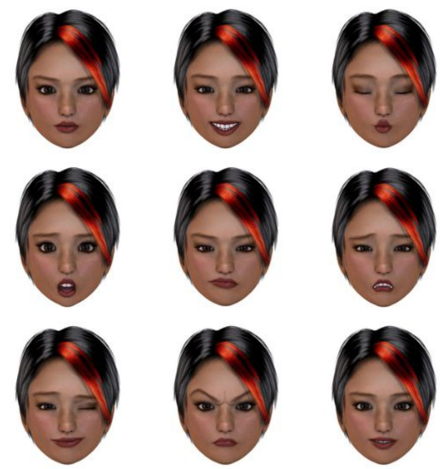
Globally, more than 3 billion people play video games and spend more than $50 billion annually on in-game purchases.[24] Using virtual reality goggles and advanced 3D graphics, video gamers can now inhabit realistic worlds where they socialize, are entertained, and create new digital environments. Many take on the persona of a character (called an "avatar") and spend money earned in the game on wardrobes and accessories (known as "skins") for their virtual selves.

Figure 42. Online Avatar

Source: Zepeto app

Figure 43. Computer-Generated Humans with Expression



Source: Shutterstock

That in-game economy is now emerging into the physical world through the Metaverse, a burgeoning network of immersive media platforms. Many of the world's largest technology and social media companies are betting that the Metaverse represents the future of the internet.[25] Facebook CEO Mark Zuckerberg describes it as a place where "instead of just viewing content, you are in it. And you feel present with other people as if you were in other places, having different experiences that you couldn't necessarily do on a 2D app or webpage."[26]

[24] "Number of video gamers worldwide in 2021, by region," Statista, August 2021; "Consumer Spending on In-game Purchases Worldwide from 2020 to 2025", Statista, May 2021.
[25] Dalvin Brown, "Big Tech Wants to Build the 'Metaverse.' What on Earth Does That Mean?" *The Washington Post*, August 30, 2021.
[26] Casey Newton, "Mark in the Metaverse," The Verge July 22, 2021.

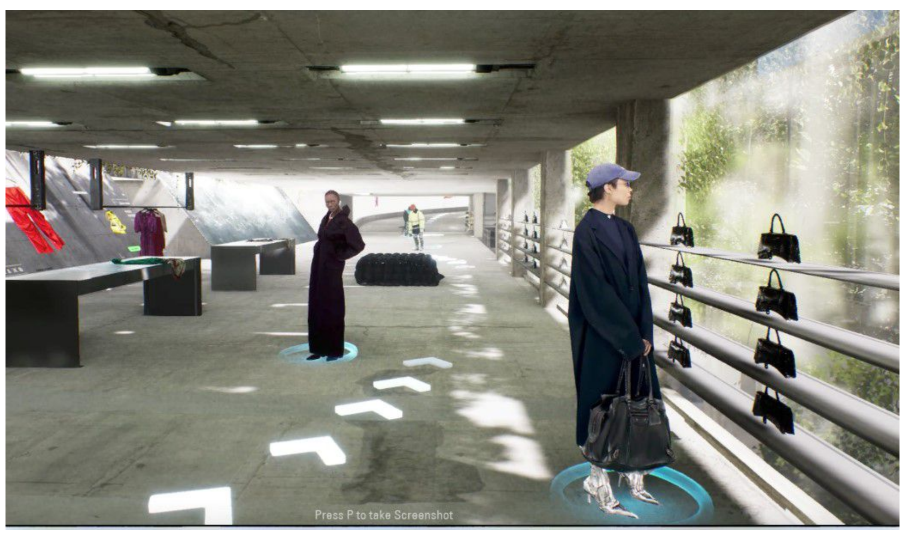
Travis Scott and Ariana Grande have performed in the Metaverse — attracting millions of concertgoers and generating an estimated $20 million apiece.[27] A major American entertainment studio is exploring how to “take its entire canon…into mixed reality to be consumed on next-gen immersive displays.”[28] Simultaneously, tech entrepreneurs and established retail brands are creating integrated shopping experiences that bridge the digital world and the real one. In this Metaverse Mall, users’ avatars are “metahumans” — realistic facsimiles of themselves that can interact with the virtual environment, socialize with friends, and try out and buy products.[29]

Welcome to the Metaverse Mall

The Metaverse Mall has the potential to overcome the shortcomings of offline and online shopping by merging them into a seamless, immersive experience that blends an in-store experience with the convenience of e-commerce — sprinkled with endless imagination.

It will consist of virtual stores where brands sell both digital and physical products to consumers who split their time between these two worlds. We can think of it as the evolution of the Direct-to-Consumer (D2C) model — except products will play only one part while experiences take an increasingly important role. Like social media, the Metaverse will have a massive impact on marketing as it enables a shift from traditional advertising to more immersive, engaging brand experiences. Imagine entering a shopping mall, looking for a pair of skis, and being virtually transported to Mont Blanc where a team of designers describe everything about the skis while you take them out on the slopes.

Figure 44. Balenciaga presented its latest collection in a video game, “Afterworld: The Edge of Tomorrow,” a collaboration with Epic Games’ creation software Unreal Engine. Players are assigned an avatar designed by the brand and have 20 minutes to traverse five levels to see the full collection and a vision of the year 2031.



Source: Balenciaga

[27] Taylor Hatmaker, “Fortnite’s Ariana Grande Concert Offers a Taste of Music in the Metaverse,” TechCrunch, August 9, 2021.
[28] Adrian Pennington, “How Do You Map the Metaverse? Ask Ted Schilowitz,” NAB Amplify, accessed October 8, 2021.
[29] Christopher Travers, “Unreal Engine’s MetaHuman Creator, Analyzed and Explained,” Virtual Humans, February 17, 2021.

High-end fashion and streetwear brands are paving the way for this new, avatar-first economy. "Younger generations evolve in a fluid digital world in which the boundaries between their physical and online lives have converged," said Michaela Larosse, Head of Content & Strategy at The Fabricant.[30] "Dressing up their digital self to hang out on digital platforms is real life for them. In this scenario, screenwear becomes the new streetwear."

The next iteration of D2C will open new revenue streams for companies:

- **Direct-to-Avatar (D2A):** Selling products such as skins and digital fashion, art, and collectibles directly to avatars outside the gaming environment.
- **Direct-to-Metahuman (D2M):** Here, a consumer will be able to see a digital twin of himself or herself try on clothes to check the fit and the look. They can then purchase the physical item, which will be shipped to them, as well as a virtual version for their metahuman twin to wear. This next-gen online shopping experience is a "try it before you buy it" model that avoids ordering a product online to try at home only to ultimately return it — which is both inconvenient and environmentally unfriendly.

The move to the Metaverse Mall will happen incrementally, but the potential to disrupt traditional industries is limitless. Today, one startup is developing "the world's first retail marketplace through games and allowing brands to sell and ship direct to game players," while another builds computer-generated imagery (CGI) store platforms for major fashion and beauty brands.[31] Meanwhile, retail brands are extending their market reach by selling digital cosmetics and shoes for avatars, creating one-of-a-kind digital collectibles, and using augmented reality software to sell (real) furniture, watches, and lipstick.[32]

[30] Camila Straschnoy, "Direct to Avatar Economy in the Metaverse," LinkedIn, June 1, 2021.
[31] See the Scuti and Obsess websites.
[32] Jeremy White, "IKEA's Revamped AR App Lets You Design Entire Rooms," *Wired*, April 20, 2021.

Figure 45. Evolution of Commerce

Name	DIRECT-TO-CONSUMER (D2C)	DIRECT-TO-AVATAR (D2A)	DIRECT-TO-METAHUMAN (D2M)
Description	Selling physical products directly to the end consumer. D2C brands are responsible for managing their own inventory, fulfilment & shipping	Selling products such as skins and digital fashion, art, and collectibles directly to avatars	Selling physical and digital products directly to digital-humans for use in both virtual and real worlds
Medium	Internet /.com	AR, VR, MR, 3D	
Type of products	Physical	Digital (e.g., fashion for avatars, art and collectibles)	Digital + Physical (e.g., fashion, furniture, beauty, automotive, etc)
Benefits to Brands	- Expand brand reach and control the brand story - Offer broader product assortment - Improve engagement with customers	- Reach new generations of customers - Shift from selling items to selling *creativity* - Tell unique stories through immersive experiences - Experiences can be hyper-personalized - Limitless possibilities for sustainability-focused brands	
Benefits to Consumers	- Convenience and ease of purchasing . . . but no ability to try the product before purchasing resulting in high volume of returns and unsustainable practices	- Allow for greater self-expression and creativity - "Try before you buy" increases the chance of purchase and reduces the volume of returns - *Consumption as access rather than possession* is changing the paradigm of consumerism and reducing the impact on the environment	

Source: Citi Ventures

Blockchain, NFTs, and Virtual Stores

The rise of blockchain and cryptocurrencies is also paving the way for virtual economies to expand beyond gaming and evolve into the Metaverse Mall. Non-fungible tokens (NFTs) are making it easier to buy and sell digital products because they can certify that items including images, video, audio, collectibles, digital art and fashion, and virtual real estate are one-of-a-kind — leading to the creation of brand-new markets in the Metaverse.[33] NFT sales reached $2.5 billion in the first half of 2021, compared to $13.7 million in all of 2020.[34]

In Decentraland, a digital world built on the Ethereum blockchain, investors can buy virtual property with MANA, a cryptocurrency that can be purchased on trading apps.[35] Sotheby's has a gallery there, and blockchain protocol Boson paid $704,000 to establish retail space where people buy digital assets that can be exchanged for physical goods and services.[36]

[33] For more on NFTs, see City Ventures, "NFTs and the Dawn of the Metaverse," April 6, 2021.
[34] "NFT Market Hits $2.5 Billion in Six Months," PYMTS.com, July 6, 2021.
[35] "Investing in Decentraland in 2021," Republic, September 17, 2021.
[36] "Sotheby's Opens a Virtual Gallery in Decentraland," Decentraland blog, June 4, 2021; Cameron Thompson, "Boson Pays Record $704K for Decentraland Plot to Create a Virtual Mall," CoinDesk, June 9, 2021.

Clearly, we are in the early days of the Metaverse and its potential and disruptive power are, as yet, unclear. This has not, however, stopped private industry from experimenting, innovating, and investing trillions of dollars to be part of it.[37]

Figure 46. Virtual Fashion and Collectibles, Merging Realities in Fashion and Gaming

Source: RTFKT

Seven Layers of the Metaverse

American entrepreneur, author, and game designer Jon Radoff says the Metaverse value chain encompasses seven elements:[38]

1. **Infrastructure:** The technologies that power our devices, connect us to the network, and deliver content will need to be more powerful and smaller to deliver the Metaverse of the future.

2. **Human interface:** Tech-enabled wearables will bring us closer to the Metaverse through further miniaturization, sensors, embedded AI technology, and low latency.

3. **Decentralization:** A decentralized system is scalable and promotes experimentation and growth.

[37] Jon Radoff, "The Metaverse Value-Chain," Medium, April 7, 2021.
[38] Ibid.

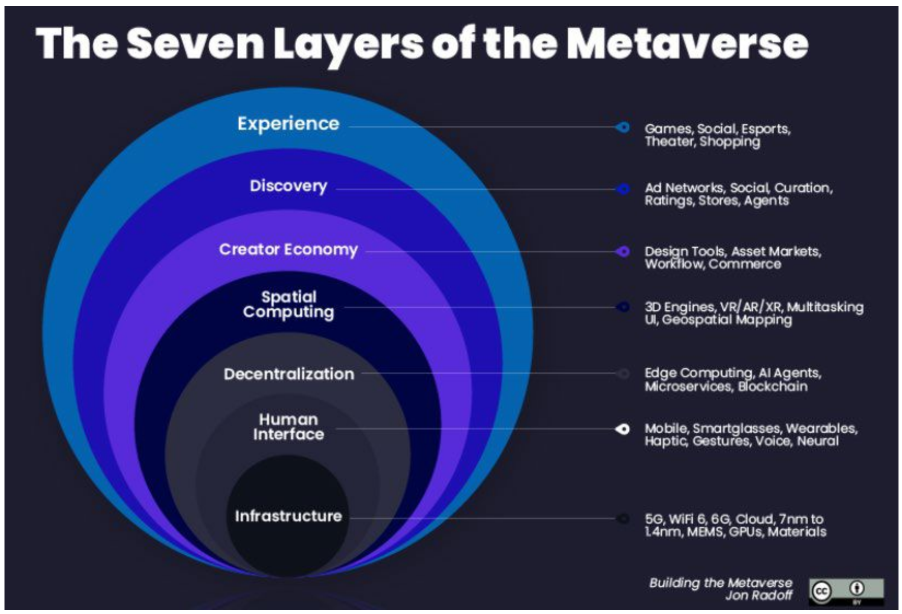
4. **Spatial computing:** Software will erode the barriers between the physical world and the Metaverse. This includes 3D engines, geospatial mapping, voice and gesture recognition, and next-gen user interfaces.

5. **Creator economy:** Radoff and other evangelists envision the Metaverse democratizing the creation of digital experiences. “Not only are the experiences of the Metaverse becoming increasingly immersive, social, and real-time,” he writes, “but the number of creators who craft them is increasing exponentially.”

6. **Discovery:** This is the process of introducing people to experiences in the Metaverse.

7. **Experience:** The Metaverse is neither tethered to nor restricted by physical space, distance, or objects — which can make previously scarce experiences more widely available. In the Metaverse, everyone can have a front-row seat at the theater. “Traditional industries such as travel, education, and live performance will be reshaped around game-thinking and the economy of abundance,” Radoff writes.

Figure 47. Building the Metaverse



Source: Building the Metaverse, Jon Radoff

Virtual Money, Real Money

There are no solid projections of the future size or value of the Metaverse Mall, even as it evolves in plain sight on our game consoles, computers, and devices. However, data from the entertainment, social media, online retail, and videogame software and hardware industries hint at its massive potential.

Bloomberg Intelligence says the Metaverse opportunity was about $500 billion in 2020 and is poised to reach $800 billion by 2024 (a 5-year compound annual growth rate of 13.1%).[39] As video games continue to evolve to more closely mimic the real world, their market opportunity will expand to include live entertainment, including concerts and sporting events, as well as a share of social media advertising revenue. And this does not begin to capture the massive potential from supporting infrastructure (e.g., computing, networking, and financial services) and the Metaverse Mall that is radically changing the way we shop while disrupting traditional and nascent industries.

Barriers to Adoption

New technologies, protocols, companies, creators, and discoveries are needed to deliver on the promise of the Metaverse.

- **Infrastructure and hardware:** A fully-realized, global Metaverse will require improved computing power; lower-latency infrastructure; and greater internet availability, speed, and concurrency. Advances in virtual reality and augmented reality hardware and software are also key to optimizing the immersive experience.
- **Interoperability and openness:** Another essential element of the Metaverse is the ability to take products, information, and services across platforms and between the digital and physical worlds. For this to happen, the Metaverse needs to be open, interoperable, and not dominated by a single entity. Currently, most Metaverses are controlled by large companies and lack interoperability between platforms. Ideally, companies will acknowledge the value of and need for open-source systems and will cooperate on common standards to allow people to travel between virtual worlds without changing identities or losing money or digital assets.

Closing the Gap and Leading the Way

Ultimately, the Metaverse Mall is a new marketing and sales channel with the potential to radically change how brands interact with their customers. In the coming years, innovators across industries and disciplines will close the gap between virtual and physical realities — with a strong push from young digital natives who already spend a lot of time in digital gaming environments. Chances are good that these generations will be the first in line at the Metaverse Mall.

[39] Mario Stefanidis, "Roundhill's Intro to the Metaverse," Roundhill Investments, June 24, 2021.

Non-Fungible Tokens

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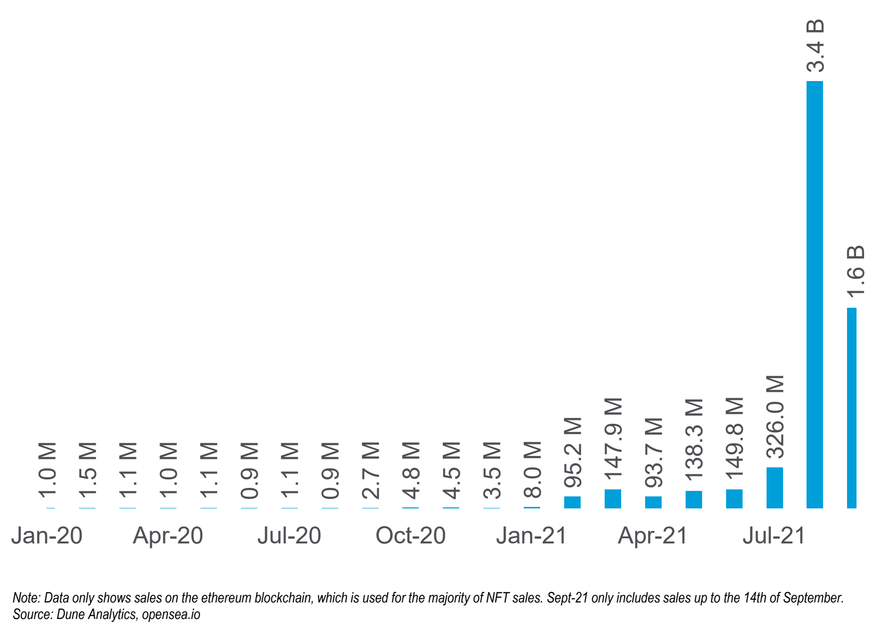
2021 has seen an explosion in interest in non-fungible tokens (NFTs). Traded volumes of NFTs have soared with their total market value hitting $37 billion in 2021 versus $2 billion in December 2020. Timelines are awash with articles explaining what NFTs are and their history, news items about family offices creating dedicated teams focusing on crypto assets, as well as general interest stories on the hundreds of use cases ranging from the sublime (digital art) to the absurd (digital pets). As one might expect, there is also no shortage of commentary about the likely outlook for this new innovation, with some hailing it as a completely new paradigm — quite literally Internet 3.0 — and others, equally vociferous in articulating their skepticism. We examine what NFTs are as well as their history, their use cases, and their potential drawbacks before considering potential winners and losers from their longer-term widespread adoption.

Figure 48. Monthly NFT Sales Volume on OpenSea Marketplace, US$m



Note: Data only shows sales on the ethereum blockchain, which is used for the majority of NFT sales. Sept-21 only includes sales up to the 14th of September
Source: Dune Analytics, opensea.io

What Is an NFT?

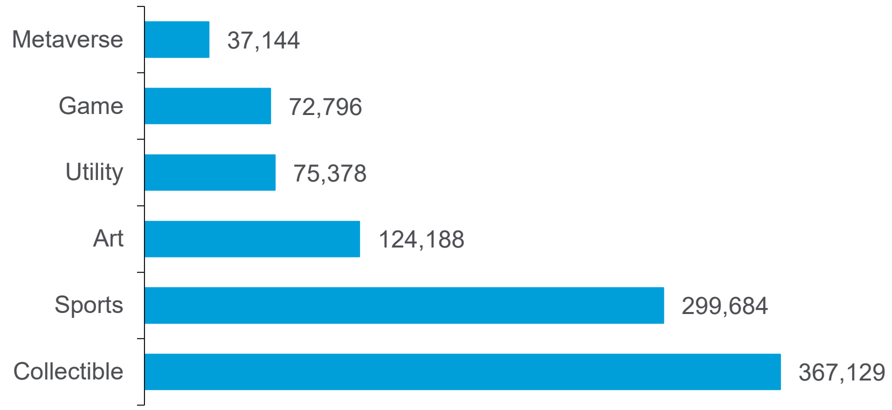
A non-fungible token (NFT), or Nifty, is a cryptographic asset (i.e., a transferable digital representation utilizing cryptography in order to prohibit copying, duplication, or counterfeiting). It is recorded on a blockchain, also called distributed ledger technology — a digital system storing encrypted blocks of data and recording their provenance — with unique identification codes and metadata that are not interchangeable (hence the term "non-fungible") and certify authenticity and ownership.

Cryptocurrencies, such as Bitcoins, are another famous type of cryptographic asset recorded on a blockchain. However unlike NFTs, they are fungible, meaning you can exchange one for another without any noticeable difference, as they are all equivalent.

NFTs can be used to represent real-world items and collectibles ranging from art, fashion, luxury, sports, gaming, and music to real estate, licenses and certifications, personal identities, tweets, rarities, and even the NFT's own definition — in short, anything you can imagine.

The market for NFTs therefore attracts a broad range of individuals and institutions: artists, investors, collectors, technology geeks, aesthetes, governments, corporates, influencers, celebrities, and most recently financial analysts.

Figure 49. Number of NFT Sales in Popular Categories, 1H2021



Note: Data only shows sales on the Ethereum blockchain, which is used for the majority of NFT sales. Data does not include sales which take place "off-chain."
Source: NonFungible.com

A Brief History

While NFT as a term was only coined in 2017, its history can be traced back to 2012 when the Colored Coins project opened the way for experimentation within the crypto ecosystem.

The aim of Colored Coins was to use Bitcoin's blockchain for assets such as digital collectibles, coupons, in-game items, company shares, property, and access tokens. However, Bitcoin's scripting language was inadequate and limited the sustainability of the application.

A few years later in 2014, Counterparty — a peer-to-peer financial platform and open-source protocol constructed on top of the Bitcoin blockchain — succeeded in reducing some of the limitations and developed the idea initiated by Colored Coins. Users were then able to create their own tradable assets or currencies, and in 2016 the famous meme "Rare Pepes," featuring a frog character and considered to be the first real cryptoart project, was launched on the platform.

In 2017, Ethereum emerged as another popular choice with cryptocurrency and blockchain market participants, and Rare Pepes began trading on that platform as well. Thereafter the first "real" NFT projects emerged: (1) CryptoPunks — offering 10,000 unique digital characters that were then traded amongst users, and (2) CryptoKitties — a virtual game to adopt, raise, breed, and trade digital cats with their own unique DNA. These projects brought NFTs to the mainstream.

In the period since, the NFT ecosystem has continued to evolve, coming to mass prominence in 2021 with several high-profile NFT transactions capturing the public's imagination. NFTs are now seeing widespread use in the arts, video games, marketing, and even fast food, as well as becoming a material asset class in their own right — Reuters reported $2.5 billion of sales in the first half of 2021 versus just $13.7 million in the first half of 2020.

Selected Glossary:

DeFi or Decentralized finance: Global peer-to-peer financial applications and services on public blockchains disrupting traditional financial intermediaries.

Mining: The process of verifying and recording transactions on a blockchain in order to receive rewards (usually in the form of cryptocurrencies) by solving energy-intensive computational puzzles via the Proof-of-Work protocol.

Minting: Same as staking except that it also includes the act of verifying and validating transactions in order to receive additional rewards.

Proof-of-Work: Consensus algorithm securing cryptocurrencies on a blockchain via the use of expensive, time- and energy-consuming computational power.

Proof-of-Stake: Consensus algorithm securing cryptocurrencies on a blockchain via the use of an original stake in the cryptocurrency in proportion to their holdings.

Sharding: Horizontal partition of a logical database (division of its rows into distinct independent tables) in order to spread out the computational and storage workload across the network.

Staking: Act of locking cryptocurrencies in order to receive rewards but in a less resource-intensive way than mining thanks to the Proof-of-Stake protocol.

Why Are NFTs Important?

We identify two key stakeholders for whom the advent of NFTs is potentially very significant.

- **Creators:** For owners of intellectual property (IP), the main advantage of a decentralized ecosystem distributed on the blockchain is that it not only offers new pathways for creators to monetize their content but also allows them to retain a greater share of the economics. This is done by reducing the take rate, or even entirely cutting out traditional intermediaries, whether it be agents, art galleries, record labels, or traditional streaming services. Critically, NFTs allow content owners (if they want) to retain future economic participation in the value of their IP, such that when assets are resold/traded in the future they can create additional revenue streams.

- **Consumers:** Despite much of the furor about the perceived futility of owning digital assets, for buyers of NFTs there are a number of benefits. By definition, as a non-fungible token, NFTs are unique. This does not, of course, necessarily mean they are rare, but this uniqueness makes them inherently collectible for anyone interested in that space. Notwithstanding their digital nature, the NFTs may also have utility, giving the user additional powers in a video game, giving them exclusive listening rights to a particular recording or, simply, giving them the pleasure of knowing they own a unique piece of art.

Finally, and perhaps most importantly, they are re-sellable (both “as created” and after having been “sharded”), meaning that when the utility of the NFT starts to fade (or its traded value goes up), there is the chance to sell the NFT and recoup the original investment.

NFTs can therefore be deployed in any number of environments and, in each ecosystem, create a direct relationship between content owner and consumer.

Example Use Cases

Video Games: F1 Delta Time and The Sandbox

Within video games, blockchain offers the potential to enhance users’ experience by improving and expanding a system that actually already exists. The concept of in-game money clearly already exists and has been around for some time, but once purchased ceases to have any value outside of the context of the original game and is sometimes difficult to transfer to other users. The use of blockchain technology now makes this process easier, faster, and more importantly, more secure by tokenizing the in-game currency and content as an NFT.

- **F1 Delta Time** is an interesting example of how individualized NFTs — created within the context of a mobile racing game — can be traded within or even outside the game environment. The sale of the game’s first official NFT asset — the completely unique virtual F1 car named “1-1-1” for slightly more than $100,000 in an auction — is an interesting validation of the perceived attractiveness of usable NFTs in a video game setting.

- **The Sandbox** is a Metaverse concept whereby an entire immersive three-dimensional virtual world has been registered on a blockchain with the aim that elements of it can be bought and sold, and used to host user-generated content. Although the landscape has seen early success as big brands have bought space in the virtual world, it has still been designed in a way that makes it accessible to the average everyday user to facilitate the creation of content. It was also designed with the intent that the underlying asset — the virtual real estate in the Sandbox world — not only has utility, but has scarcity and is tradable. What makes it interesting is that, unlike other crypto asset classes, real estate can be developed and used, or simply bought and sold as the gamer/owner sees fit.

Figure 50. F1 Delta Time – An Official Formula 1 Blockchain Game

Source: Animoca Brands

Figure 51. The Sandbox Metaverse Concept

Source: Animoca Brands

Music

Next-generation streaming services use blockchain technology for royalty payments. They are also a platform for artists to create NFTs based on their music. These NFTs are split into two categories: (1) Listening Rights NFTs, whereby individual recordings are split into ownable/tradeable tokens; and (2) Royalty Income NFTs, whereby the NFT denotes ownership of a share of the underlying IP of a particular track and owners take a share of any income stream created by the IP.

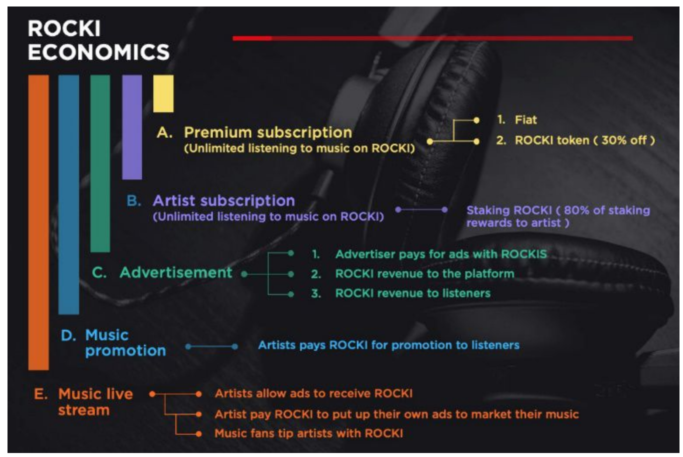
By creating a mode of fair remuneration and direct exchange between musicians and their listeners, the model paves the way for artists to not only maximize their income but retain a greater share of it. Importantly, the model ensures their artistic creations are better protected thanks to ownership tracking and the security and transparency provided by blockchain.

Figure 52. Rocki – Uses of Tokens/NFTs in Music Streaming

Old Way		New Way
Intermediaries	⇨	Direct listener to artist relationships
Pirated product	⇨	NFT for owner copyrights & earnings
Fraud & inconsistency	⇨	Transparency and security by blockchain
FANS not incentivized	⇨	Tokenomics benefits all

Source: Rocki, Citi Research

Figure 53. Working Towards A New Music Ecosystem



Source: Rocki

Complications

NFTs and blockchains are fascinating, innovative technologies that are disrupting multiple sectors. Unfortunately, this disruption also comes with some concerning side effects, ranging from environmental and social issues to regulatory and legal concerns.

Environmental Concerns

One of the most alarming side effects of blockchains, and consequently NFTs, is their environmental footprint. Blockchains require mining (i.e., the process of recording and verifying transactions on a blockchain done via Proof-of-Work) and minting (i.e., the process of validating information, creating a new block, and recording it into the blockchain done via Proof-of-Stake), which both require large amounts of energy. Subsequently, high volume daily trading of the NFTs created also increases energy usage, as each transaction requires more energy to be properly validated. The environmental impact from this energy usage — in terms of carbon and other greenhouse gas emissions — is significant.

To put it in perspective, minting a cryptoart NFT on the blockchain could be equivalent to weeks, months or even years of an average citizen's energy consumption in a developed country.

This raises ethical concerns given the resulting asset is not even "real." It is important to note that mining/NFT minting becomes harder to perform the more it is done, which is basically how the system works and its products gain value; therefore, this energy consumption is only likely to increase over time.

There is, however, some scope for change. An important notion to understand with NFTs is that most of the energy waste is a function of the Proof-of-Work (PoW) protocol, which requires extensive computational effort and energy to be expended in order to solve arbitrary mathematical puzzles. These puzzles exist to prevent fraud or hacking and get harder and harder to solve over time, requiring higher computational power and energy use. The Proof-of-Stake (PoS) protocol, by contrast, relies on the existing stake one individual has and requires substantially less computational power to validate crypto asset ownership. PoS has been estimated to reduce carbon and other greenhouse gases emissions relating to mining by 99% compared to PoW.

Ethereum — the most popular blockchain technology used by NFTs — is planning a transition from PoW to the more environmentally sustainable PoS consensus algorithm in its Ethereum 2.0 upgrade. It has already launched a beta service and a full launch is anticipated by the end of 2021 or early 2022.

Figure 54. Blockchain Technologies in NFTs — Bitcoin vs. Ethereum

BLOCKCHAIN	PROS	CONS
Bitcoin	• Most famous and recognized blockchain, primarily due to its cryptocurrency • Much longer tenure in the market	• Limited blockchain technology, not sufficient for certain NFT projects • Energy inefficient and becoming even more so over time • Slow transactions, getting even slower • High volatility in the cryptocurrency
Ethereum	• Most used blockchain for NFTs • Good platform for NFTs based on improved blockchain technology and smart contracts (may contain executable code) • Transitioning to PoS, a more environmental-friendly algorithm (99% less emissions) • Fast transactions	• Platform still working mostly on PoW, and therefore energy inefficient • PoS won't be implemented before some time (end 2021-22), and even then, it will take time to be properly mastered as a new mechanism • High volatility of the cryptocurrency and therefore of the NFTs based on Ether

Source: Bloomberg Citi Research

Regulatory and Legal Concerns

A key feature of cryptocurrency and subsequently NFTs is the almost complete absence of any regulatory or legal framework to monitor or govern their use. This makes the ecosystem potentially very attractive to criminals (including, but not limited to, money launderers, terrorists, tax evaders, and fraudsters) given its built-in anonymity, absence of controls and checks, absence of due diligence, lack of monitoring, lack of transparency, and the ease of manipulating prices.

Notwithstanding these, despite being "unregulated," market participants are not completely above the law. Common areas where traditional laws come into conflict with the crypto world include:

- **Content rights:** Before NFTs are minted, creators need to have all proper approvals from the relevant rights holders (e.g., creators, collaborators) and all contractual terms then need to be made clear upfront to the NFT's buyer. If this process is not properly done, it can lead to costly disputes with both the rights holders and NFTs purchasers, especially if access to the royalty stream is ultimately removed.

- **Securities law:** As NFTs share characteristics with other digital investment vehicles, some may legally be considered securities by the Securities and Exchange Commission (SEC) on a case-by-case basis, particularly those that implicate rights to future profits. In this context, it seems likely trading these assets may become subject to insider trading rules at some point in the future.[40]

- **Anti-money laundering and sanctions law:** Given their inherent anonymity and price volatility, NFTs may be an attractive vehicle for money launderers. Issuers should avoid unknowingly selling NFTs to individuals located in countries sanctioned by the U.S. government, as this would be a violation of federal law.

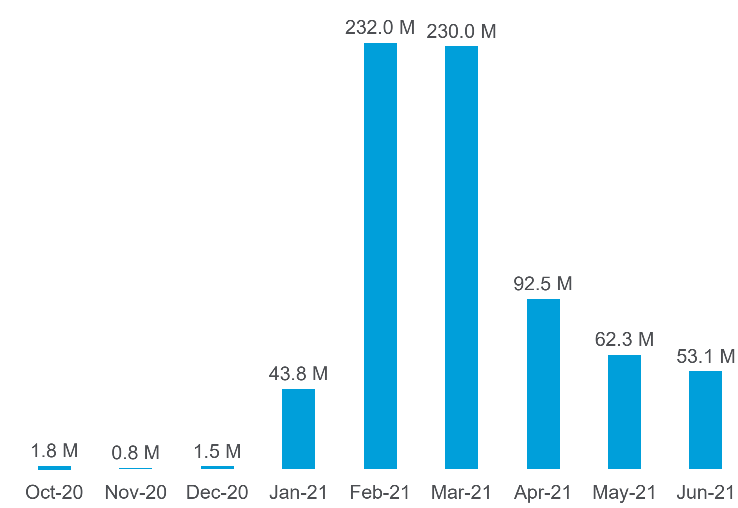
- **Taxation and crypto currency volatility:** As with other investments, market participants in NFTs should expect to pay various type of taxes including income taxes and capital gains taxes, which can be quite unpredictable and high given NFTs' volatility. What is more, as cryptocurrencies are subject to their own taxation regime and since NFTs tend to be traded through them, it is also important to be aware of all the tax implications.

- **Non-U.S. legal risks**: What makes NFTs and similar decentralized investments even more complex is their global/cross-border nature. As different legal systems and jurisdictions govern different geographies and countries, the risk of unintended violations of the law increases.

Financial Concerns

There is widespread concern that NFTs, alongside cryptocurrencies, are a speculative asset class. The current period of hyper-speculative activity — potentially fueled by boredom over lockdown, massive government stimulus, and zero interest rates is at best likely to fade over time, and at worst, may result in severe financial losses for some market participants.

Figure 55. A Cautionary Tale: Monthly Sales Volume on NBA Top Shot, US$m



Note: includes primary and secondary market sales. NBA Top Shot sales are on the Flow blockchain.
Source: NBA Top Shot

[40] For an interesting discussion of this point, see '"OpenSea Admits NFT Insider's Trading Incident," *Financial Times*, September 15, 2021.

Financial concerns are difficult to dismiss entirely. We do know that levels of activity are elevated — one online trading business indicated that about 65% of its crypto trading revenue in the second quarter of 2021 came from Dogecoin. But just because there is a lot of activity that may result in some investors (or speculators) losing money does not necessarily mean that the entire ecosystem is economically unsustainable. As one observer argues, it is simply that it is yet to reach "equilibrium."[41]

Potential Winners and Losers

Looking at the implications for various sectors, we argue the application of NFTs are significant, particularly in the media and leisure industries, by providing material and potentially entirely additive revenue opportunities in areas like licensing and merchandising.

In practice, this means the potential short-term winners from the advent and growth in NFTs is literally any person or organization who owns content and/or has a brand. An NFT can be created on this content or brand, which in turn can be staked (i.e., effectively lent to third parties to earn a yield), traded (i.e., bought and sold), or sharded (i.e., broken up into smaller tokens) while continuing to retain some utility.

This might include collectibles within the context of a video game or a music streaming service. It might be digital art. It might even, in time, be a digital equivalent of the toys kids receive with their Happy Meal or tickets for a big football game.[42]

Potential losers, by contrast, are any and all traditional intermediaries. In music this does not necessarily mean labels will become redundant because there will always be value in artist discovery and management, but making money in distribution and/or royalty collection may become more challenging over time. Similarly, in video games it is the digital gatekeepers — the digital storefronts who at present enjoy significant take rates on transactions that take place within their ecosystems — who are potentially most at risk from widespread adoption of NFTs.

More broadly, one might argue that traditional distribution businesses including video and music streaming companies may become more challenged, as will the walled gardens in the internet ecosystem that currently have an enormous amount of control over what the consumer sees, interacts with, and purchases. And all of this is before considering the potential challenges for the banking sector as a consequence of decentralized finance (DeFi). (For more information on DeFi, please see the Citi GPS reports *Future of Money* and *Bitcoin*. [43]

[41] Jon Jordan, "Blockchain Games Vs Pyramid Schemes," GamesTX, September 9, 2021.
[42] Tickets to events provide an interesting real-world parallel to NFTs in the sense that they are something that is both collectible and has utility.
[43] For more discussion of the potential longer term implications of the rise of crypto on the broader financial services ecosystem, see Citi Markets – Business Advisory Services, "Key Innovations and Emerging Developments in Digital Assets and Decentralized Finance — A Primer," August 2021; Citi Markets – Business Advisory Services, *Industry Revolution Volume IV - The Convergence of the Crypto and Traditional Economies: How Investment Managers Can Deliver Value in a Decentralized "NewFi" World*, June 2021; and Citi Research, "Global Financials Insights – DeFi & NFTs: Expanding the Crypto Universe," May 4, 2021.

Notwithstanding the market's relatively early stage of development, and the important side effects and risks associated with the space, we think NFTs and the blockchain technologies underpinning them are a technological innovation that cannot be ignored by investors, companies, and consumers alike.

Can Psychedelic Drugs Cure the Mental Health Crisis?

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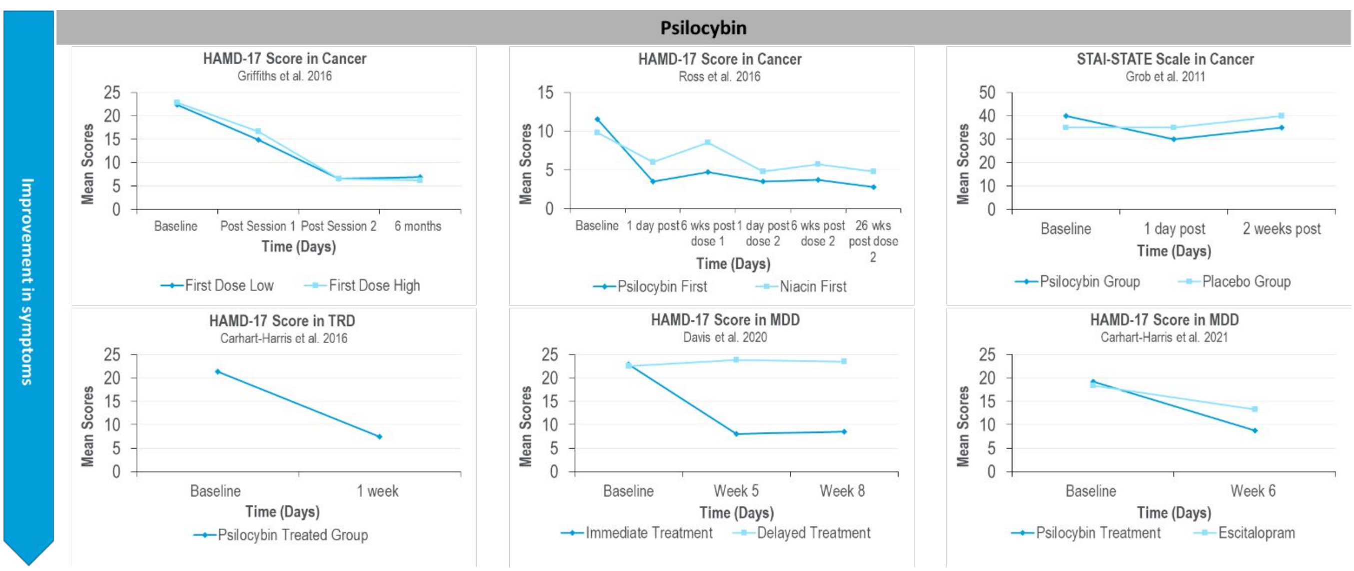
Psychedelic drugs — such as LSD, psilocybin (the hallucinogen in "magic mushrooms"), and DMT (the hallucinogen in ayahuasca) — have a long history in addressing mental health disorders, including schizophrenia, stress, anxiety, depression, and addiction. In the 1950s, anecdotal evidence pointing to a potential therapeutic benefit from psychedelics prompted early adoption of psychedelic-assisted psychotherapy. However, formal clinical research on psychedelics was largely halted in the U.S. in the 1960s by federal regulations, prompting a period of recreational use without stringent physician oversight. The signing of the Controlled Substances Act in 1970 formally banned psychedelic drugs for medical and recreational purposes, largely due to their perceived abuse liability.

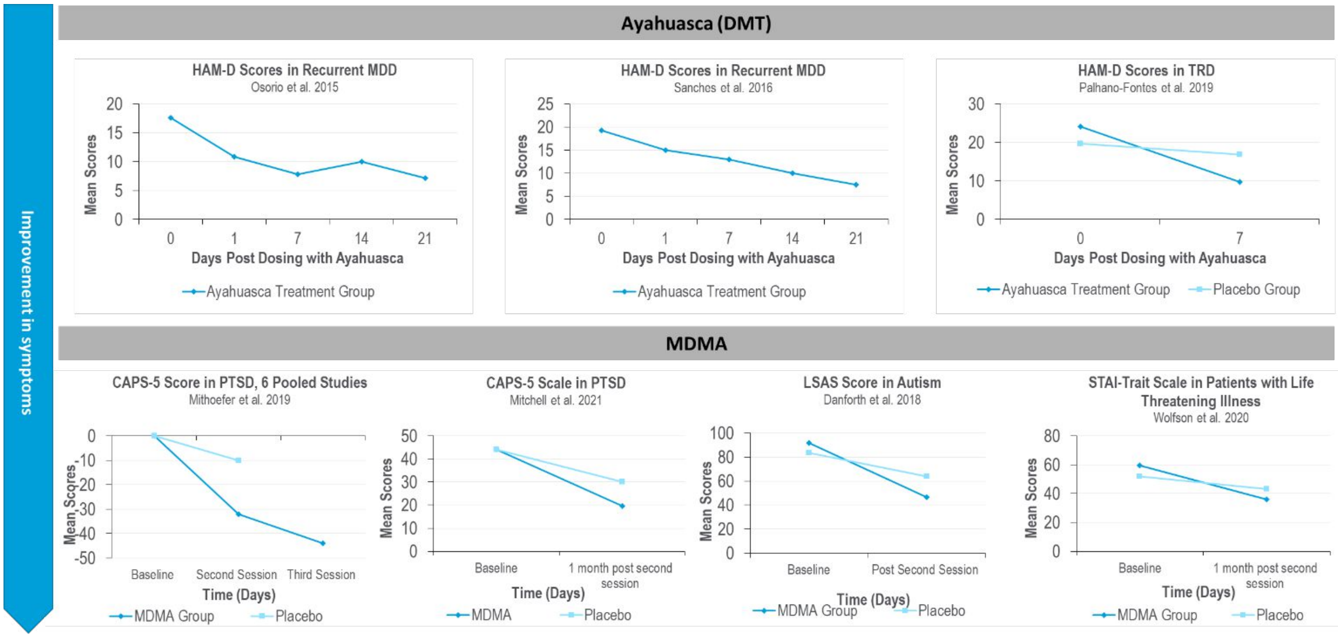
In the last ~20-25 years, formal clinical studies sponsored by academic institutions have been able to get up and running for drugs like LSD, psilocybin, DMT, ketamine, and MDMA (ecstasy) in mental health conditions. Results have consistently shown rapid and meaningful treatment benefits when administered in a controlled setting under supervision of a healthcare provider, as shown in Figure 57 with lower mean scores indicates improvement.

Figure 56. Efficacy Data from Investigator-Initiated Studies with Psychedelic Medicines



Source: Citi Research

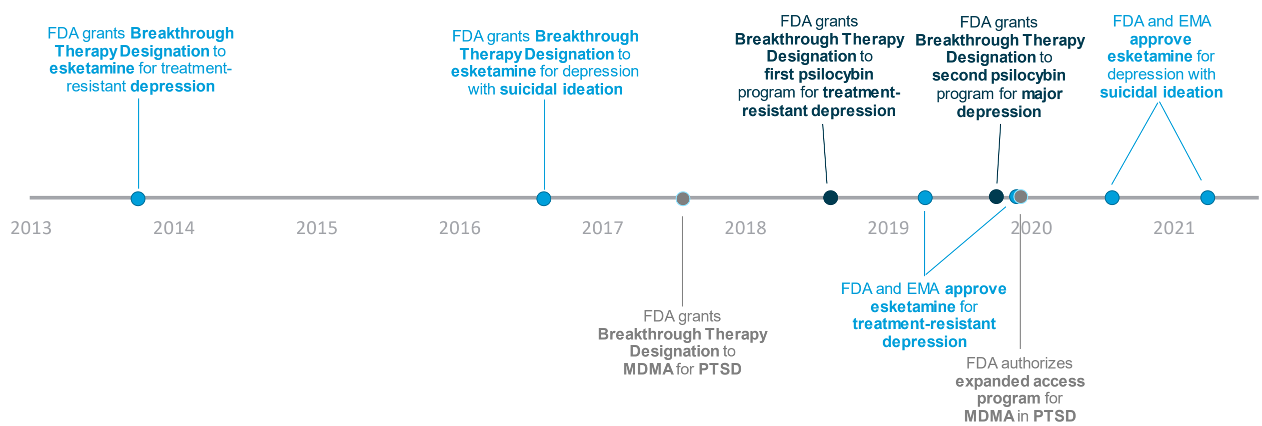
Figure 57. Efficacy Data from Investigator-Initiated Studies with Psychedelic Medicines (cont…)



Source: Citi Research

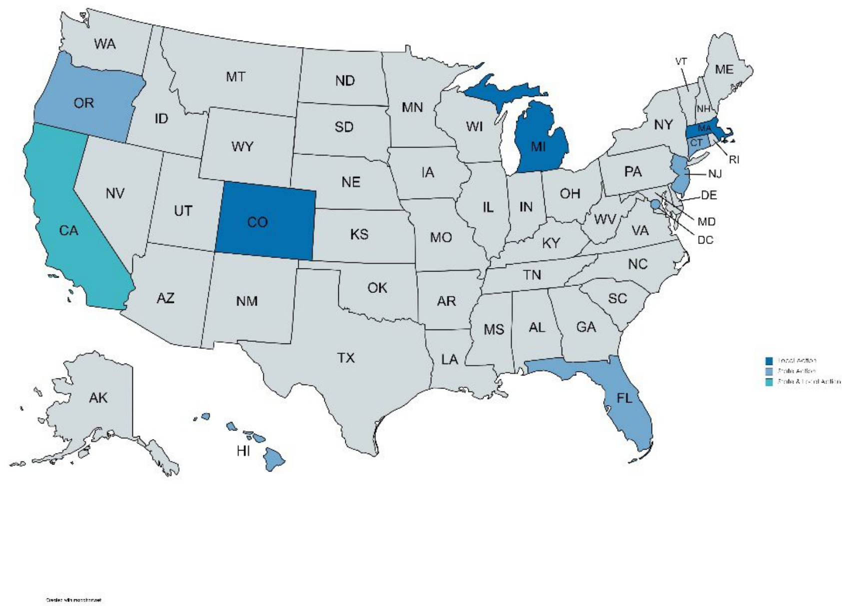
Strength of data from these studies has prompted a few key developments: (1) improved regulatory flexibility (see Figure 58), (2) formal psychedelic decriminalization/legalization efforts in certain states and cities in the U.S. for medical and/or recreational use (see Figure 59), and (3) the emergence of a host of companies developing psychedelics for commercialization for mental health conditions (see Figure 60for an overview of the pipeline of psychedelics in development for medical uses). Six psychedelic companies are trading on NASDAQ/NYSE as of mid-September 2021, with multiple others on deck.

Figure 58. Recent Regulatory Updates for Psychedelics



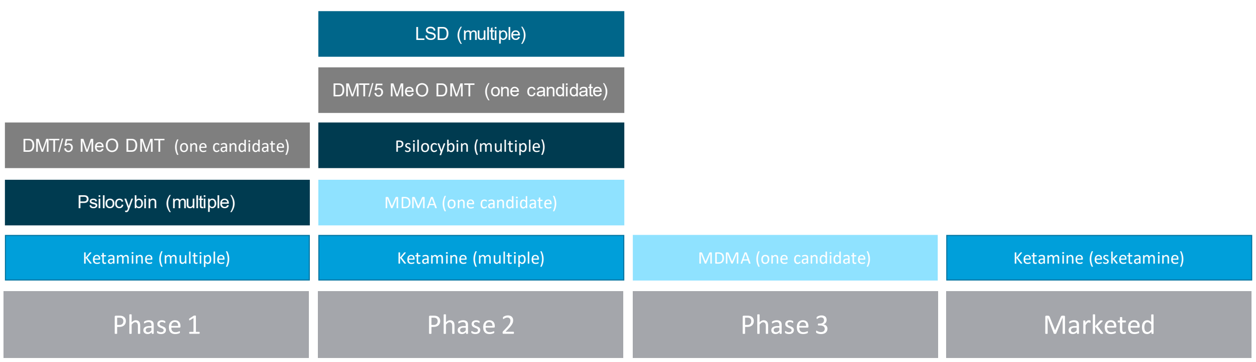
Source: Citi Research

Figure 59. U.S. State and Local Governmental Actions Around Psychedelic Drugs



Source: Citi Research

Figure 60. Current Psychedelic Drug Development Pipeline



Source: Citi Research

As shown above, the first "psychedelic" (a formulation of ketamine and esketamine, a ketamine derivative) was approved by the U.S. Food & Drug Administration (FDA) and the EU's European Medicines Agency (EMA) in 2019 for treatment-resistant depression. Of the ongoing clinical programs for the more classical psychedelics (LSD, psilocybin, DMT), the most near-term potential approvals are: (1) MDMA for post-traumatic stress disorder (PTSD), with a potential U.S. launch in 2023; and (2) psilocybin for treatment-resistant depression, with a potential U.S. launch in 2024 or early 2025.

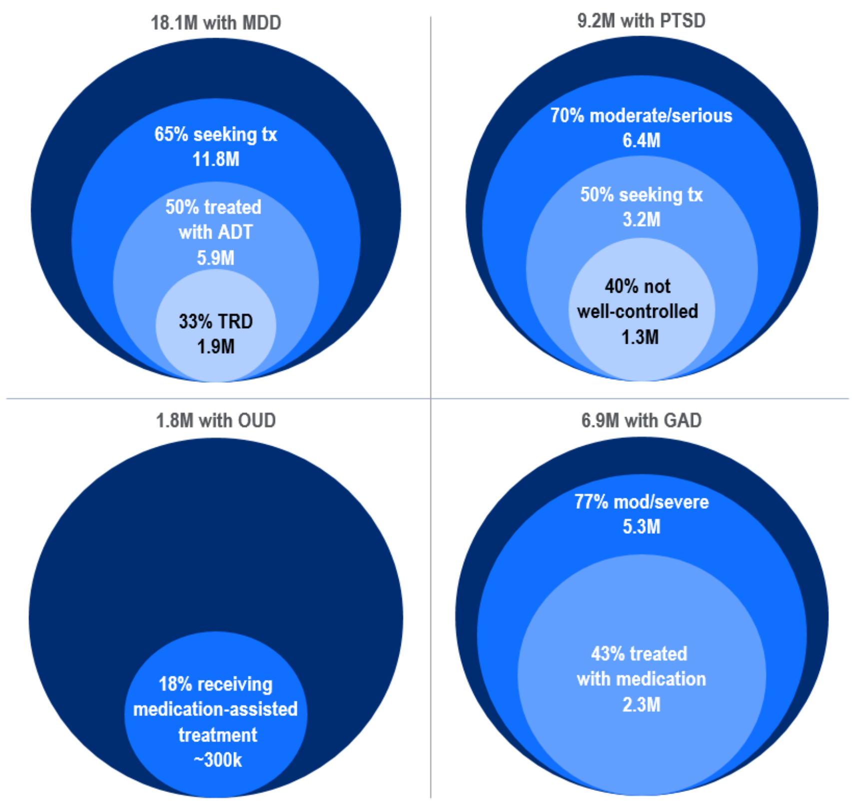
Psychedelics Could Be Big…

The current mental health crisis is an epidemic, affecting millions of people worldwide. Most psychedelics are in development for depression (ketamine, psilocybin, DMT); post-traumatic stress disorder (MDMA); substance use disorder, including opioid use disorder (ketamine, MDMA, and ibogaine); and anxiety (LSD).

Though there are available therapies for these conditions, response rates are generally low. For example, approximately one-third of patients with depression who are treated with an antidepressant have treatment-resistant disease, meaning they have tried and failed two or more separate classes of medications.

Additionally, innovation in mental health has been limited. Most drugs in development are either reformulations of existing drugs or show only a marginal benefit over generic options. Existing drugs also come with a host of side effects, including weight gain, sexual dysfunction, and more. As such, the mental health space is in desperate need of novel, high-efficacy, and safe therapies, and psychedelic medicines could launch into blockbuster ($1 billion+ in annual sales) or mega-blockbuster markets.

Figure 61. Citi Estimated Addressable U.S. Market Opportunity for Psychedelic Drugs



Note: MDD = major depressive disorder, TRD = treatment-resistant depression, ADT = antidepressant therapy, PTSD = post-traumatic stress disorder, OUD = opioid use disorder, GAD = generalized anxiety disorder

Source: Citi Research; NSDUH; NIMH; SARDAA; CDC; WHO

…If the Commercial Model Is Viable

Despite the unmet need in mental health, strong data to date for psychedelic drugs, and an improved regulatory and governmental backdrop surrounding psychedelics, the key outstanding question is whether or not psychedelics will be prescribed if approved due to: (1) stigma around history of psychedelic drugs and (2) stringent monitoring requirements likely to be placed on psychedelic drugs by regulators due to concerns around safety and abuse potential.

As noted earlier, safety and evidence of efficacy for psychedelic drugs is strongest when administered under care of a physician as part of a psychotherapy program. In current clinical trials for psychedelic medicines, patients undergo three stages in the treatment process: (1) preparation, (2) dosing, and (3) integration (follow-up). The dosing session can last between 6-8 hours, with each preparation and integration session lasting 60-90 minutes. This is a significant time commitment for both the physician/healthcare provider (HCP) and the patient.

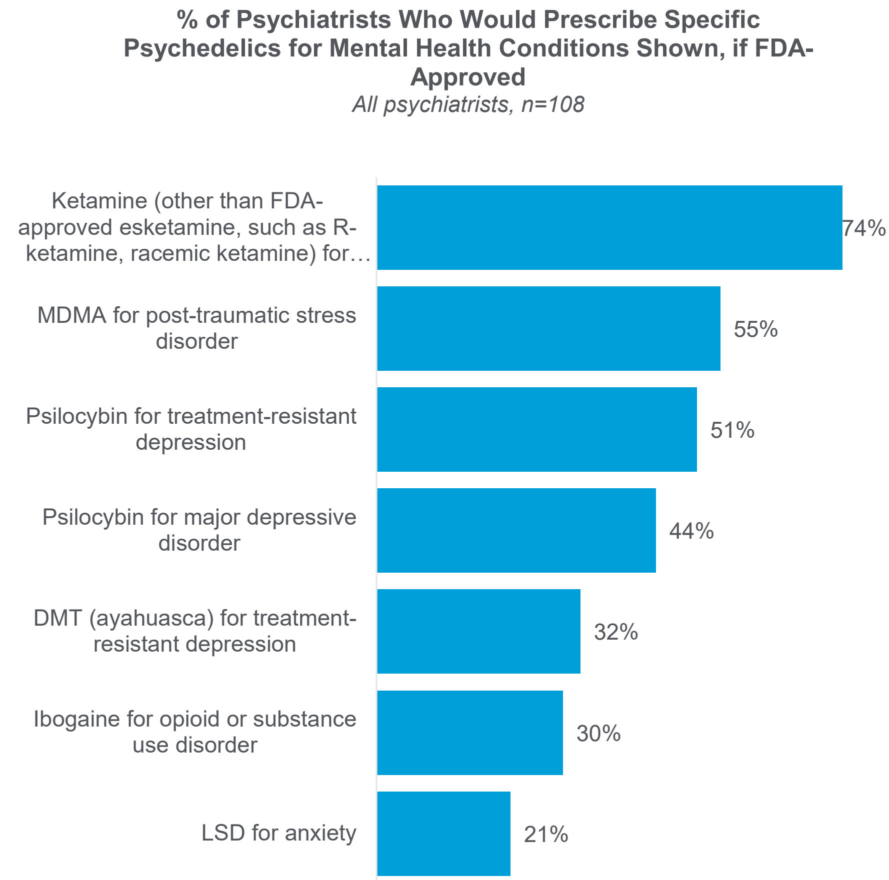
It also presents a logistical challenge given that HCPs must receive special training on the prep, dosing, and integration process for each psychedelic drug they wish to prescribe. HCPs will also need to provide a physical space for patient observation during the 6-8 hour dosing session.

We recently conducted a survey of 108 psychiatrists in the U.S. to understand how willing they were to prescribe psychedelic drugs, if approved, given these potential logistical hurdles.[44] As shown in Figure 62, the majority of psychiatrists are willing to prescribe psychedelics. Ketamine, MDMA, and psilocybin are of greatest interest. For treatment-resistant depression, surveyed psychiatrists estimated that they would prescribe ketamine to ~23% of their patients, followed by psilocybin (~13%) and DMT (~12%). For PTSD, they indicated they would prescribe MDMA to ~16% of their patients. If those estimates come to fruition, hundreds of thousands of patients in the U.S. could ultimately try psychedelic medicines if approved.

[44] For further survey results see Citi Research, "ATAI & CMPS: Psychedelics and Mental Health," July 13, 2021.

Figure 62. Intent to Prescribe Specific Psychedelics if FDA Approved for Specific Indications (all, n=108)

Q: If the following psychedelic drugs are ultimately approved by FDA for the indications shown below, would you be willing to prescribe them to your patients? Select all that apply



Source: Citi Research, survey of n=108 US psychiatrists; survey conducted online from May 7-12, 2021

Conclusion

Despite the stigma around psychedelic drugs, an improving regulatory and governmental backdrop, compelling clinical data, and a public health crisis in mental health are driving a resurgence of interest in psychedelic drugs for medical uses. Success could trigger a paradigm shift in how mental health conditions are treated.

Travel of the Future

AI-Driven Aviation Surveillance for Monitoring Infection Risks

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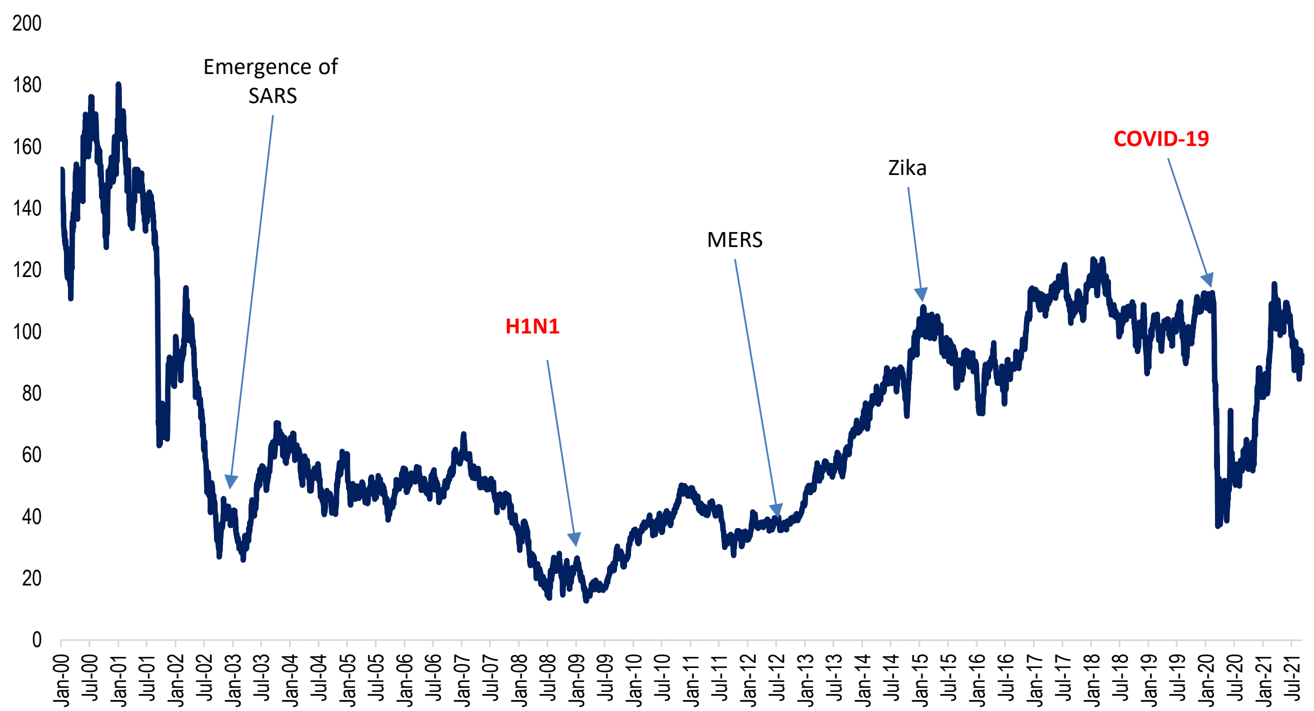
As the U.S. government provided billions in financial aid to the airline sector, the industry also took swift measures to show consumers they care about customer and employee health and well-being. These pandemic-era initiatives included installing HEPA (High Efficiency Particulate Air) filters on aircraft, blocking middle seats (at least for some time), reducing direct contact between passengers and crewmembers via the restriction of on-board services, and requiring all on board to wear masks.

Against this backdrop, it seems unlikely that the end of COVID-19 should mark the end of all pandemics/epidemics to come. Figure 63 shows the COVID-19 pandemic had a lopsided impact on the Americas XAL Airline Index. Although several other disease outbreaks directly influenced at least parts of the Americas — including H1N1 actually being the only other recent episode that qualified as a pandemic — COVID-19 had the deepest impact on the industry.

Figure 63. It Seems Unlikely that COVID0-19 Would Mark the End of All Pandemics



Source: Citi Research, Bloomberg, Medicalnewstoday.com

In conjunction with enhanced early warning systems, airport screening could intensify, with artificial intelligence (AI)-controlled screening systems monitoring passengers' body temperatures and other identifiable vital signs in order to prevent infected individuals from embarking and disembarking.

The rollout of AI airport screening systems could be slower in the developing world, but similar on-board AI-monitoring systems on aircraft serving non-monitored international airports could help determine whether one or more passengers is infected, in addition to predicting the extent to which the pathogen might be highly contagious. These systems could help airlines and health authorities determine whether to quarantine an entire plane in the event that the systems detect dangerous, highly contagious pathogens on board.

AI Could Also Support Baggage Screening

Several years ago, on a business trip to Colombia, it was interesting to note that higher-end hotels and parking garages had uniformed guards patrolling with bomb-sniffing dogs. Although this level of surveillance looked impressive, one of the guards had stated, “After 90 minutes, the dogs’ detection capabilities start becoming less effective.”

Going forward, the aviation industry and/or related tech companies could increase the penetration of AI-driven luggage/cargo surveillance. This technology could extend beyond the simple security screens at airport check points and could include baggage screening equipment as luggage enters cargo holds, along with follow-up screening once customers collect their luggage prior to clearing immigration and customs upon disembarking.

These enhanced surveillance techniques could detect a multitude of things, ranging from bomb-making materials, illegal chemicals, unlicensed weapons, and disease agents to unstable batteries/chargers, plastic weapons, and bed bug infestations in luggage. Airlines could offset some of the costs by charging passengers extra fees for enhanced screening.

Robotic Air Marshals

In August 2021, the U.S. Federal Aviation Administration (FAA) reported it had received more than 3,000 complaints about unruly passengers so far this year. According to the report, roughly 2,300 of these complaints involved passengers’ refusal to wear face masks. However, some of these incidents were violent and the FAA mentioned that it has identified potential violations of federal rules in 465 cases so far. In a normal year, the agency typically takes enforcement actions on 150 cases.

In addition to simply scanning for sick passengers and prohibited items in carry-on bags, robotic air marshals could monitor potentially dangerous passengers, including terrorists/criminals; mentally and/or emotionally unstable passengers; and those under the influence who are acting aggressively. Robotic air marshals could obtain passenger reads from on-board scanners that would relay everything from passengers’ body temperature; hear, respiration, and perspiration rates; and pupil dilation — to individuals arguing with flight crews or other passengers.

Any of the above incidents that pass certain thresholds could trigger robotic air marshals to issue warnings or even subdue non-compliant individuals through non-lethal means. However, the introduction of robotic air marshals would need to be done with caution and consideration as their use could open a host of ethical questions around racial profiling and the overreach of technology.

AI Surveillance Is a Probable, Long-Term Development But the Technology Is Known Today

Within the aviation industry, digitization and automation has long been part of the picture. This includes the use of auto pilot systems, fly-by-wire technology, and anti-collision software. Fly-by-wire involves the use of redundant computer programs, which regulate the pilot's commands/navigational entries and how the aircraft actually responds to those commands. For instance, the system would correct a plane's trajectory in the event that a pilot's actions risked pulling the aircraft into a stall.

Against this backdrop, the industry probably needs at least several years to develop and implement some forms of AI surveillance. Factors affecting the speed of uptake include the capability of putting on-board AI sensors and robotic air marshals that are durable and cost-effective, and do not significantly add to aircraft take-off weight. The latter is a critical factor in airline economics — heavier aircraft burn more fuel and could eventually face more maintenance costs, as their engines need to run at higher rates to operate at the same cruising speeds.

There are companies today that manufacture robotic security guards and in a few cases, robotic security guards patrol offices and malls. However, many of the current technology robots are bulky and heavy, so the development of on-board versions of these systems could take time. Incorporating disease detection capabilities into robotic air marshals could also involve at least a few years of development, even though the medical community currently uses some AI to diagnose illnesses.

On the other hand, the addition of AI systems in airports could happen somewhat more quickly — perhaps within the next three to five years. Airport screening areas are less constrained and some airports around the world already have significant passenger screening in place, including body temperature scanners that have popped up during the pandemic.

Automation Technology Is Not New to Aviation

Statistically speaking, commercial flights are already one of the safest passenger transportation modes. In October 2020, a U.S. Department of Defense (DOD) study assigned a low risk designation to on-board transmission of COVID-19. Among other factors, the industry's use of HEPA (High Efficiency Particulate Air) filters has helped reduce risks for passengers. The DOD study determined that an individual would have to remain seated next to an infectious passenger for at least 54 hours in order to receive a dangerous dose of virus through the air.

Looking beyond disease risks, it is also worth noting aviation's very good safety record versus other passenger transportation modes, some of which can be attributed to automation technology. The probability of being involved in fatal accident on a commercial flight is one in 29 million, versus one in 35,000 for a trip in a private automobile or a taxi. Of course, it is inaccurate to assume that commercial airline pilots are entirely responsible for the industry's accidents and incidents. Other factors, such as unexpected weather, air traffic control errors, mechanical failures, intentional sabotage, terrorism and/or irresponsible aircraft maintenance policies can also contribute to such incidents.

For modern commercial aircraft, some degree of automation during operation has been standard for years. Commercial aircraft often operate on autopilot during long cruising periods, and many modern aircraft have digital fly-by-wire and instrument landing capabilities. Figure 64 shows the long history of automation in commercial aviation.

Figure 64. Common Flight Control Automation in the Commercial Aviation Industry

Automation	What is this?	Commercial Introduction
Fly-by-wire	Redundant computer programs that are situated between mechanical flight controls and an aircraft's actual movement	1959
Autopilot	An automatic flight control system that allows the pilot to fly the plane, without continuous hands-on control. In these instances, a pilot would typically input data such as heading, altitude, etc.	1930s
Instrument landing	An electronic system that allows and aircraft to land, even if pilots are unable to establish visual contact with the runway.	1938

Source: Flyingmag.com, Airbus, Morgridge Institute for Research, Airservicesaustralia.com, Centennialofflight.net and Citi Research

Taking this topic one step further, Citi's previous work on automation technology in aviation included the probability of the industry eventually incorporating robot/AI co-pilots. At the time of that publication — roughly five years ago — we had not expected any such implementation to occur over a ten-year span. Our primary hesitation on timelines was passenger apprehension over relying on an AI co-pilot – even in conjunction with a human captain — as well as the labor industry's probable resistance to the rollout of AI co-pilots.

Going forward, another area to watch is the industry's embrace of electric vertical takeoff and landing (eVTOL) aircraft, or air taxis. In addition to their ability to fly above congested roads and help passengers reach airports more efficiently, these vehicles could supplant auto traffic and reduce an airport catchment area's carbon footprint per capita.

There are a lot of questions relating to eVTOLs, including who would actually operate these air taxis? Also, what sort of licensing would the government require to pilot these vehicles, and what are the implications for air-to-air or air-to-ground accident rates in heavily populated urban areas? Moreover, having just one human crew member in a small air taxi instead of another revenue-generating passenger, could also have important profitability implications for the sector.

In this regard, electric air taxis might actually serve as the first step in getting the traveling public accustomed to boarding AI-piloted aircraft. A five-year rollout of AI-piloted air taxis would be consistent with Citi Research's long-term expectations around the commercial introduction of robot pilots.

Airlines, Airports and Tech Companies Win…

Global airlines, which operate across many international jurisdictions and climate zones could see the greatest benefits from the increased use of technology. Consumers would probably prefer to travel on an airline when they know a security robot is always nearby if a passenger becomes disruptive. Airports that implement such systems could also enjoy long-term brand benefits.

Developers of AI-driven surveillance systems also appear to be clear winners of these developments — provided that such developers and airlines/airports can generate an attractive return on investment on the systems.

…But Labor Could Lose

Going forward, AI-driven surveillance systems could supplant human labor. For example, on-board robots could result in less demand for the Federal Air Marshal Service. Similarly, AI-driven airport monitoring could also mean fewer employment opportunities for human baggage screeners, labor unions, airport security personnel, and others.

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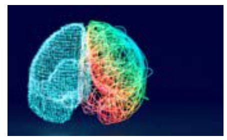

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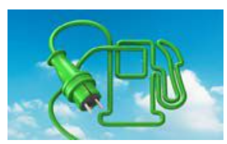

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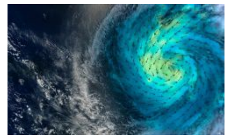

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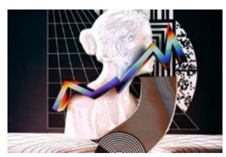

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In the fight against climate change, the world needs to reduce its greenhouse gas (GHG) emissions massively to stop the rise of the concentration of atmospheric GHGs — particularly carbon dioxide (CO_2) / One crucial approach is removing CO_2 from the air itself through: (1) nature-based solutions, including afforestation and reforestation; (2) enhanced natural processes, including land management and bioengineered plants; and (2) direct air capture.

TECHNOLOGY

Plant-based meat alternatives are already widespread, making up ~3%of the North American and European meat market in 2020. / Although currently in a nascent state, cultured meat, i.e., lab-grown "meat" produced from cells, not only provides significant ESG benefits, but also delivers better flavor over plant-based meat alternatives.