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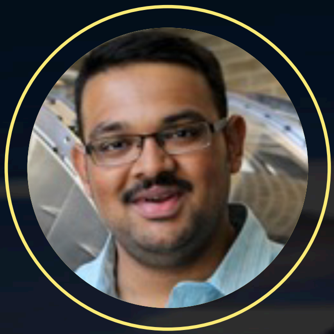
SCALING SUSTAINABLE AVIATION FUEL PRODUCTION: LESSONS LEARNED FROM EXPONENTIAL GROWTH IN RENEWABLE ENERGY INDUSTRIES

Authors



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About Boom Supersonic

Boom Supersonic is redefining commercial air travel by bringing sustainable, supersonic flight to the skies. Boom's historic commercial airliner, Overture, is designed and committed to industry-leading standards of speed, safety, and sustainability. Overture will be net-zero carbon, capable of flying on 100% sustainable aviation fuel (SAF) at twice the speed of today's fastest passenger jets. Overture's order book, including purchases and options, stands at 70 aircraft, and Boom is working with the United States Air Force for government applications of Overture.

Named one of TIME's Best Inventions of 2021, the Boom XB-1 demonstrator aircraft rolled out in 2020, and its carbon-neutral flight test program is underway. As a company, Boom achieved carbon neutrality in 2021 with a goal to be net-zero carbon by 2025. The company is backed by world-class investors, including Bessemer Venture Partners, Prime Movers Lab, Emerson Collective, and Amex Ventures.

For more information, visit **www.boomsupersonic.com**.

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Executive Summary

Air travel connects the world, linking people and enabling economies to prosper. The aviation industry recognizes that it must continue to deliver these benefits while steadily reducing its environmental impacts. The sector has committed to reaching net-zero carbon by 2050 or earlier, with many airlines committing to the Science Based Targets initiative (SBTi) and to reducing the carbon intensity of their operations by approximately 50% by 2035.

Widespread deployment of sustainable aviation fuel (SAF) is the most critical step to achieving aviation decarbonization, even with anticipated improvements in aircraft fuel efficiency and operations. To accomplish this critical need, the SAF industry must develop and scale well before 2050. While SAF production is still in its infancy, amounting to less than 0.1% of global jet fuel demand in 2021, the SAF industry is well poised to achieve exponential growth seen in other renewable energy sectors. If SAF scales at the rate of solar energy, it could reach projected international jet fuel demand by 2036 (as depicted in Figure ES-1).

This growth is necessary to address the global demand for aviation fuel with SAF in the 2030-2045 timeframe. Rapid growth is dependent on crucial early actions from industry as well as governments that provide uniform and ecosystem-wide support for SAF production and deployment.

Fig. ES-1

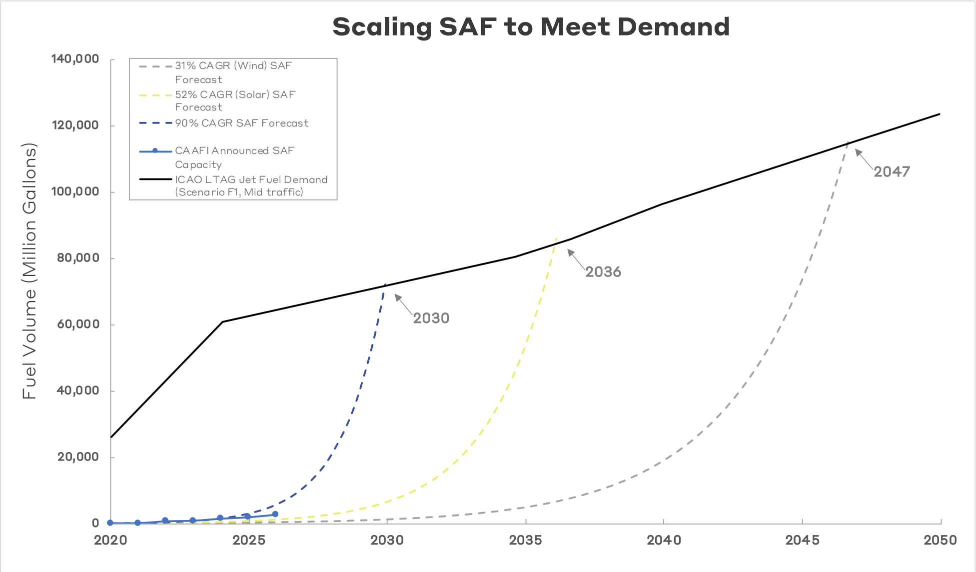


Figure ES-1: International jet fuel demand is sourced from the ICAO Long-Term Global Aspirational Goal (LTAG). Projections of exponential growth trajectories of SAF are based on a range of compound annual growth rates (CAGRs) seen in the solar and wind sectors, as well as an aspirational forecast with an optimistic growth rate. Blue dot markers indicate annual SAF production capacities that have been announced to date, as reported by the Commercial Aviation Alternative Fuels Initiative (CAAFI).

To understand how rapid scaling of SAF production can be achieved, this paper identifies key drivers that have contributed to exponential growth in other renewable energy sectors. The paper then shows how those proven trajectories can be applied to the SAF industry to support exponential scaling of production.

Exponential growth describes a phenomenon in which the growth rate of a system increases as the system increases in size. For the solar/wind electricity generation, battery storage, and renewable ground transportation fuel sectors studied in this paper, exponential growth was achieved as a result of a positive feedback loop between economies of scale and cost reductions from overcoming learning curves — as technologies are deployed, costs decrease and technology efficiency increases due to experiential learning and innovation. These improvements themselves spur further adoption of the technology. Common drivers of success in renewable energy adoption have included early demand and buy-in for the technology, government incentives, sustained R&D funding, and legislative mandates and consistent targets.

Encouragingly, the SAF industry displays hallmarks of the early stage, exponential growth patterns seen in other renewable energy industries. Industry and government have already taken impactful initial steps to foster this growth, including investing in pilot SAF production facilities; launching the SAF Grand Challenge by the U.S. government and Europe's proposed ReFuelEU Aviation initiative; signaling strong intent by airlines to purchase SAF via offtake agreements; and establishing SAF R&D initiatives (e.g., the Singapore Green Plan 2030, the Green Innovation Fund in Japan, U.S. Federal Aviation Administration (FAA) Aviation Sustainability Center (ASCENT), U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO), and the Commercial Aviation Alternative Fuels Initiative (CAAFI)). However, achieving scale requires continued commitment from industry and governments alike:

- Early buy-in and committed investments are critical to stimulating demand in the SAF market. Airlines should continue to lean in on early SAF purchase agreements, and SAF producers should continue to invest in new production facilities and to work with airlines to meet this demand. Governments should bolster demand for SAF through the expansion of early purchase commitments (e.g., for military applications). Manufacturers should support the entire SAF value chain and promote use of SAF wherever feasible, as well as ensure product compatibility with advanced SAF.

- Government incentives will be key to supporting early demand and capital investments through supplier-side tax credits (e.g., SAF Blender's Tax Credit (BTC) and Investment Tax Credits (ITC)) as well as consumer-side credits and programs.

- Continued R&D funding will be necessary to drive innovation. These programs should target reducing feedstock procurement costs and increasing conversion efficiencies; maturing emerging low- and zero-carbon SAF technologies (e.g., Power-to-Liquid (PtL) processes and cellulosic biomass); and increasing SAF blend limits.

- Finally, consistent and long-lasting policy direction is imperative for SAF scalability. Renewable fuel policies must be developed and implemented with a holistic view of the transportation industry. Policy measures should be created to promote SAF production relative to other renewable liquid fuels, given the lack of alternative decarbonization options for aviation. Low-carbon fuel programs must be expanded geographically as well to include non-biogenic and advanced biofuel SAF pathways.

Key Enablers for Scaling SAF

Early adoption, buy-in, and investment

Government incentives

Sustained R&D funding

Consistent, long-term policy

Based on the evolution of other renewable energy sectors and their ability to achieve exponential growth historically, there is ample evidence to conclude that SAF production can be rapidly scaled up to meet global aviation needs in the timeframe necessary, as long as targeted industry and government actions are taken now. These actions are crucial to enabling the aviation industry to achieve its net-zero carbon goals, and will allow aviation to continue to play its vital role in the global economy while protecting the climate.

Introduction

The global aviation industry has committed to reducing its carbon footprint, with the International Civil Aviation Organization (ICAO) agreeing to carbon-neutral growth beginning in 2020;[1] the International Air Transport Association (IATA), which represents almost 300 airlines globally, committing to achieving net-zero carbon emissions[2] by 2050; and several airlines and manufacturers committing to net-zero carbon even earlier.[3,4] Airlines around the world have committed to the Science Based Targets initiative (SBTi),[5] with pledges to reduce their operational carbon intensity by up to 50% of 2019 levels by 2035.[6] While fuel-efficient aircraft design, novel engine technologies, and operational mechanisms continue to facilitate emissions reductions, most experts agree that widespread deployment of sustainable aviation fuel (SAF) is the most critical step to achieving the carbon reduction goals of the aviation sector. [7,8,9]

What Is SAF?

SAF is a mix of hydrocarbons that is chemically similar to conventional jet fuel but is not derived from fossil fuels. SAF instead relies on carbon atoms from organic and waste materials known as feedstocks. These include waste oils, algae, forest residues, municipal solid waste, and industrial gasses, as well as atmospheric CO_2.

While fossil jet fuel and SAF produce the same amount of CO_2 emissions when combusted in the engine, the carbon atoms in SAF were already circulating in the carbon cycle — for example, SAF produced from biogenic material contains carbon that was absorbed from the atmosphere as CO_2 during plant growth. In this way, SAF forms a closed carbon loop. When carbon reductions are calculated over the fuel's entire life cycle — including emissions from extracting the feedstock, refining and transporting the fuel, and combusting the end product in a jet engine — SAF achieves a net reduction in CO_2 emissions relative to fossil jet fuel.

[1] ICAO (2019). Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change.
[2] Net-zero carbon is defined as the balancing of CO_2 emitted into the atmosphere (after CO_2 emissions have been reduced have been reduced as much as possible) with an equal amount of CO_2 that is permanently removed from the atmosphere. Source: University of Oxford Net Zero Climate.
[3] IATA (2021). Our Commitment to Fly Net Zero by 2050.
[4] Boom Supersonic (2022). 2021 Environmental Sustainability Report.
[5] SBTi (2021). Science-Based Target Setting for the Aviation Sector.
[6] American Airlines and United Airlines have committed to reducing their operational carbon footprint by 45% and 50% respectively by 2035 relative to a 2019 baseline. More than 20 airlines have made commitments to near-term (2035) carbon reductions, per SBTi.
[7] ATAG (2021). Waypoint 2050 (Second Edition).
[8] ICAO (2019). Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change.
[9] U.S. DOE (n.d.). Bioenergy Technologies Office, Sustainable Aviation Fuels.

Introduction

Decarbonizing the aviation sector will require significant quantities of low-carbon SAF. For example, the Air Transport Action Group (ATAG) estimates that between 110 billion – 150 billion gallons per year of zero-carbon SAF will be needed to achieve net-zero emissions in 2050.[10]

While SAF production remains nascent,[11] the SAF industry is poised to achieve exponential growth seen in other renewable energy sectors, but this is dependent on crucial early actions from industry partners as well as governments. Scaling up SAF production levels will require overcoming technological and policy challenges, attaining cost reduction through economies of scale and innovation, and establishing supportive regulatory frameworks.

In this paper, we study renewable energy sectors that have experienced exponential growth in production and identify the key drivers that contributed to their successful deployment. The paper concludes with recommendations for how these findings can be applied to the SAF industry and presents key enablers that are necessary to achieve a similar scaling up of SAF production.

Scaling up SAF production levels will require overcoming technological and policy challenges, attaining cost reduction through economies of scale and innovation, and establishing supportive regulatory frameworks.

[10] ATAG (2021). Waypoint 2050 (Second Edition).
[11] Per the WEF (2020) Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation report, fewer than 70 million gallons of SAF were produced globally in 2019.

The Evolution of Renewable Energy Sectors

Exponential Growth

Exponential growth describes a phenomenon in which the growth rate of a system increases as the system increases in size. This is a concept that we have all experienced. For example, 20 years ago, mobile phones were scarce, but in 2019, the number of mobile cellular subscriptions per 100 people reached 107% of the global population.[12] The number of internet users has skyrocketed by three orders of magnitude in just a few decades — just 0.05% of the world's population was online in the 1990s, compared with almost 50% by 2019.[13]

As seen in **Figure 1**, most technologies follow an "S-curve," where nascent technologies grow exponentially at the initial stages of market penetration as they catch on.[14] The rate of growth reaches a "top speed" before decelerating as the technology matures and reaches mainstream adoption, before approaching some theoretical limit (e.g., 100% of the global population, total market demand, etc.).

Fig. 1

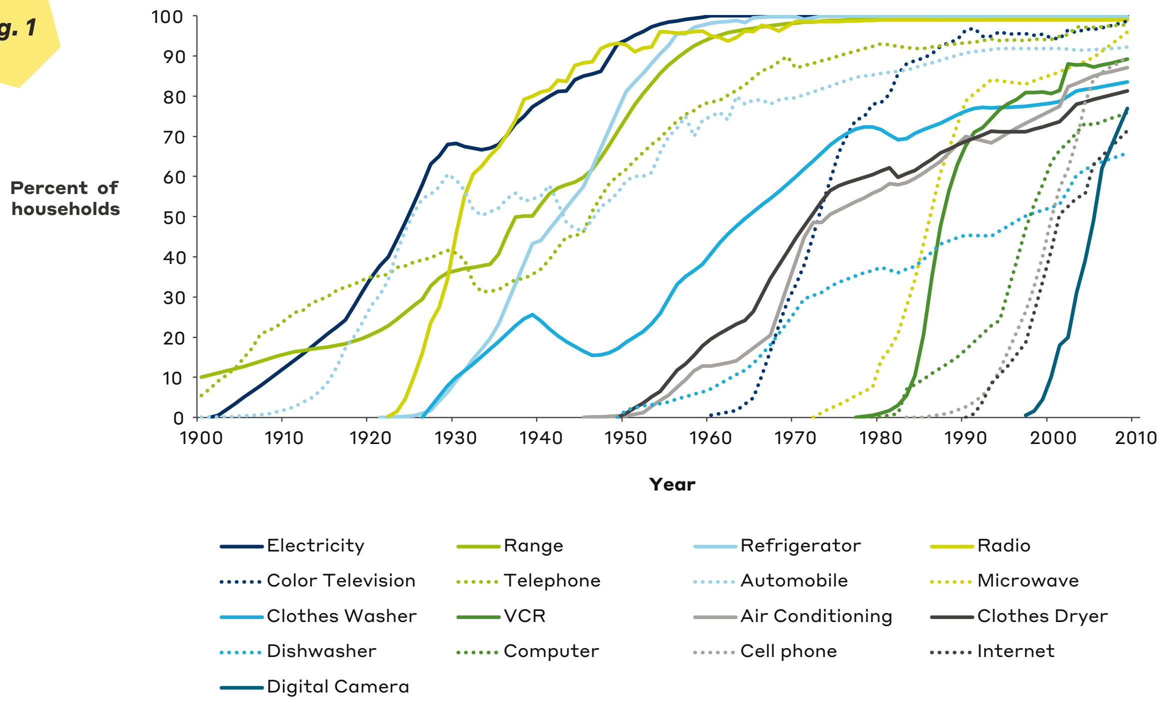


Figure 1: Historical adoption curves for new technologies in the U.S. Figure obtained from Deloitte Center for Energy Solutions (2015), US Solar Power Growth through 2040.

[12] The World Bank (n.d.). Mobile cellular subscriptions (per 100 people).
[13] Max Roser, Hannah Ritchie, and Esteban Ortiz-Ospina (2015). Internet.
[14] It is also important to note that not all technologies follow an exponential growth pattern, as seen in Figure 1.

Exponential Growth

31-52%

CAGR of solar, wind, and biofuel renewable technologies that experienced exponential growth in recent years

Recently, the world has seen exponential growth in renewable electricity generation, as seen in **Figure 2**. In 2020, about 12% of global electricity demand was met by renewable generation.[15] If renewables continue to grow at the same exponential rate as the last two decades, they could meet all of the global electricity demand by 2040. While this top-down forecast provides an illustrative outlook for renewable energy generation (and recognizes that there will be challenges in sustaining such growth), it is helpful in imagining the magnitude of progress that exponential growth trajectories can bring about.

Fig. 2

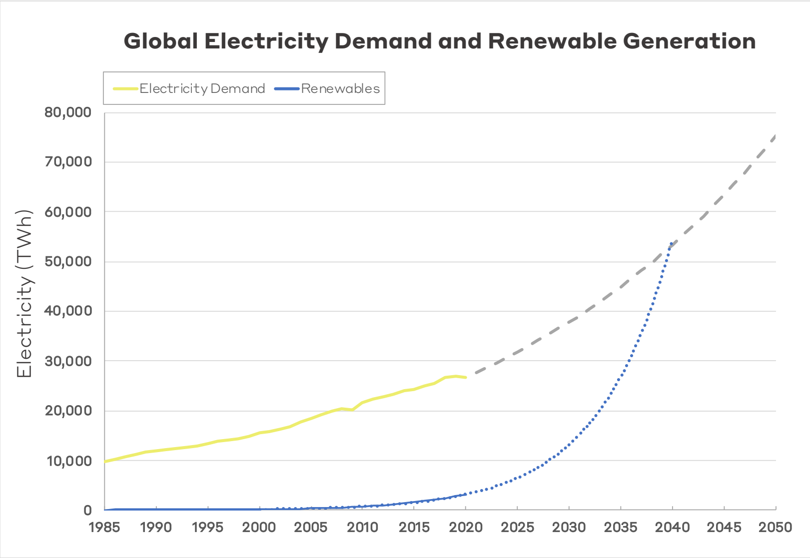


Figure 2: Global electricity demand and renewable power production (historical and projected). Historical data is from BP (2021) Statistical Review of World Energy, 70th edition. The forecast for global electricity demand assumes an annual growth rate of 3.5%, based on the average of the range of growth rates reported in McKinsey & Company (2022) Global Energy Perspective 2022, while the forecast for renewable electricity generation is based on an exponential curve fit for historical growth data between 2000 and 2020.

Focusing on individual categories of renewable energy: wind energy production worldwide began accelerating in the late 1990s; biofuel production ramped up in the mid-2000s; and solar energy production began accelerating in the past decade, as shown in **Figure 3** below. During the 10-year period of maximum growth, these technologies grew at a compound annual growth rate (CAGR) of 31-52%. The production of battery energy storage systems (BESS), while still nascent, has exhibited a strong growth rate of 66% CAGR between 2013–2020 and is expected to continue expanding at a CAGR of 31% in the coming years.[16]

[15] BP (2021). Statistical Review of World Energy, 70th edition. Renewable generation sources include wind, geothermal, solar, biomass, and waste, and exclude nuclear and large hydroelectric power.
[16] Wood Mackenzie (2020). Global energy storage capacity to grow at CAGR of 31% to 2030.

Fig. 3

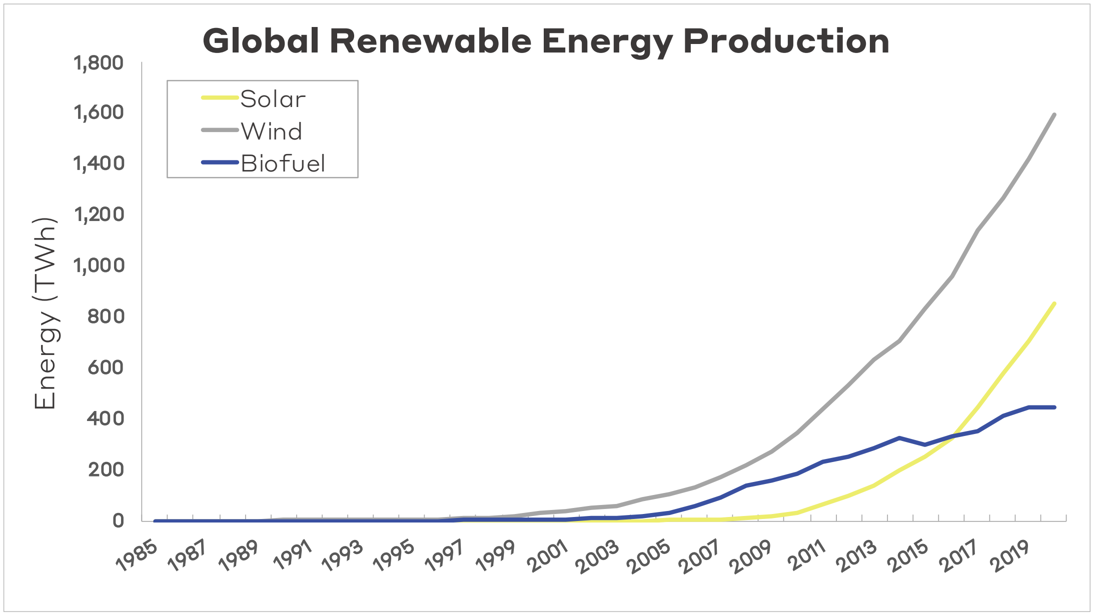
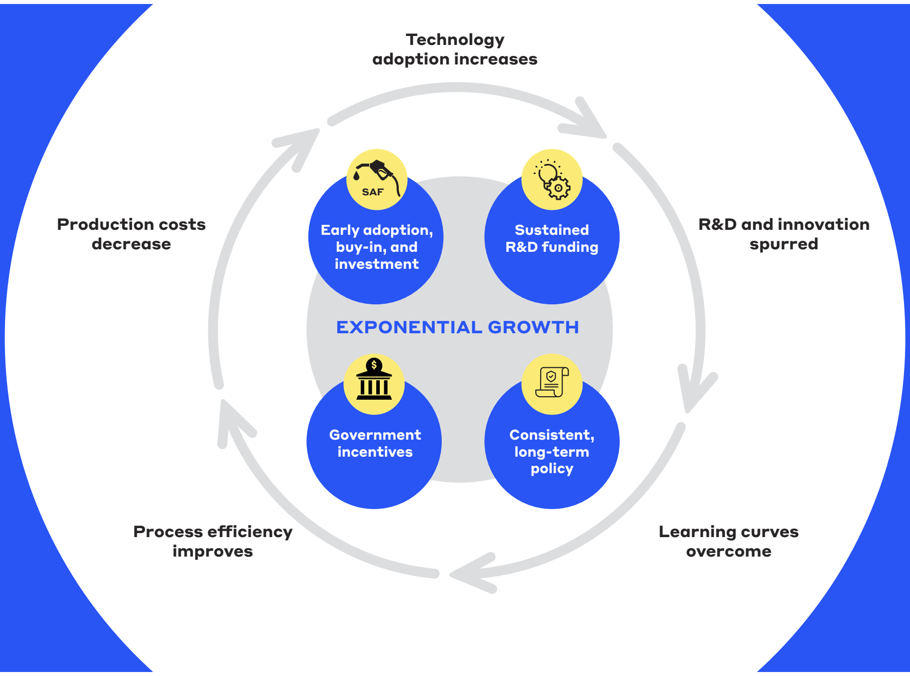


Figure 3: Global energy production for three renewable energy technologies: solar electricity generation, wind electricity generation, and biofuel production. Data from BP (2021) Statistical Review of World Energy, 70th edition.

In this paper, we study the evolution of these four renewable energy industries and identify key drivers that have contributed to their exponential growth. We then discuss how these findings can be applied to the SAF industry and present the key enablers necessary to achieve similar scaling in SAF production.

KEY DRIVERS TO ENABLE AN EXPONENTIAL GROWTH IN RENEWABLE ENERGY

We studied the evolution of four renewable energy industries — solar, wind, batteries, and biofuel — and identified core drivers that have contributed to the success of their exponential growth. To achieve similar economies of scale in SAF production, four key enablers are required to create a positive feedback loop and accelerate its momentum.



Solar and Wind Power Generation

The two most important reasons behind the exponential proliferation of solar and wind electricity generation capacity are (1) cost reductions in technology and (2) continued improvement in efficiency.[17,18]

Exponential cost reductions are realized as producers overcome the learning curve. This phenomenon of "learning by doing" is described by Wright's Law (sometimes adjusted and applied to become Swanson's Law for the solar industry).[19,20] A positive feedback loop arises — as technologies are deployed, producers accumulate experience that reduces material and manufacturing costs. Competition accelerates innovation for greater efficiency and novel approaches. These in turn enhance the attractiveness of the technology and spur further adoption.

There are numerous examples of Wright's Law in the renewable energy industry:

- Solar panel module costs have been declining at a rate of approximately 20% with each doubling of cumulative solar deployment.[21,22]
- Solar and wind levelized costs of energy have consequently decreased by between 30-40% with each doubling of cumulative solar deployment.[23,24] Just in the past decade alone, levelized costs of electricity (LCOE) for solar power have seen rapid reduction by a factor of almost 7 (see **Figure 4**). LCOE for wind power (which attained scale earlier than solar power) continues to reduce, dropping by a factor of 2 between 2010 and 2020. Renewable electricity costs have reached record lows in some parts of the world, in some cases far surpassing global median LCOE from fossil resources (e.g., coal or natural gas).[25]
- Solar photovoltaic cell efficiency has more than doubled from 22% in 1975 to 47% in 2020,[26] lowering not only material costs but also other components such as land ownership and maintenance costs.
- Similar technological improvements have also been realized in wind turbine technology (e.g., blade lengths and tower heights have increased by more than 300% since the 1990s,[27] and rotor-sweep areas have grown by nearly 600% since 1998–1999[28]). These changes have enabled wind power generation in regions previously thought to have negligible wind potential.[29]

[17] Ramez Naam (2011). The Exponential Gains in Solar Power per Dollar.
[18] Deloitte Center for Energy Solutions (2015). US Solar Power Growth through 2040.
[19] Deloitte Center for Energy Solutions (2015). US Solar Power Growth through 2040.
[20] World Resources Institute (2021). Explaining the Exponential Growth of Renewable Energy.
[21] Deloitte Center for Energy Solutions (2015). US Solar Power Growth through 2040.
[22] Hannah Ritchie and Max Roser (2021). Energy.
[23] Ramez Naam (2020). Solar's Future is Insanely Cheap.
[24] Hannah Ritchie and Max Roser (2021) – Energy.
[25] Per the International Energy Agency (IEA), the median LCOE of natural gas generation in 2020 globally was $71/MWh, while the LCOE of coal was $88/MWh. In comparison, onshore wind generation costs were as low as $29/MWh. Record low rates for solar generation have been reported at $20/MWh in Los Angeles, $13.50/MWh in Abu Dhabi and, $10.40/MWh in Saudi Arabia.
[26] NREL (n.d.). Best Research-Cell Efficiency Chart.
[27] U.S. DOE (2015). WindVision: A New Era for Wind Power in the United States.
[28] U.S. DOE (2021). Office of Energy Efficiency & Renewable Energy - Wind Turbines: the Bigger, the Better.
[29] U.S. DOE (2015). WindVision: A New Era for Wind Power in the United States.

Solar and Wind Power Generation

Fig. 4

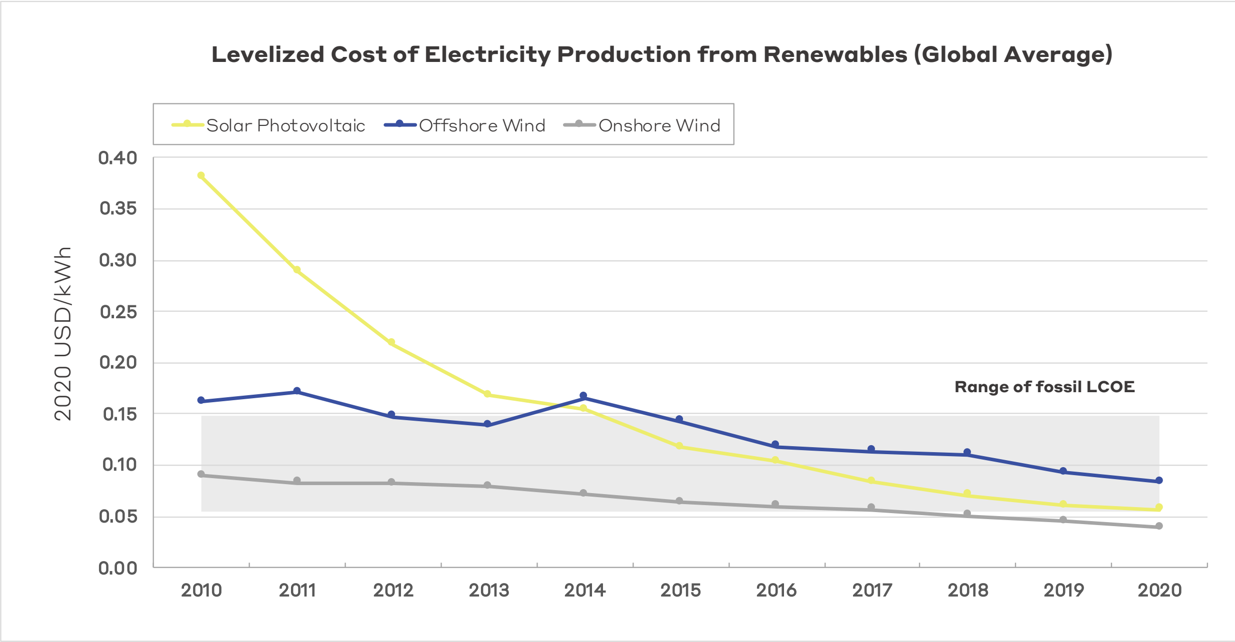


Figure 4: Trends in levelized cost of electricity (LCOE) for solar and wind power generation. Data obtained from IRENA (2021), [Renewable Power Generation Costs in 2020.]

A positive feedback loop arises — as technologies are deployed, producers accumulate experience that reduces material and manufacturing costs. Competition accelerates innovation for greater efficiency and novel approaches. These in turn enhance the attractiveness of the technology and spur further adoption.

[30] The difference between renewable energy targets and mandates is one of legal or financial liability for noncompliance. For example, Oregon and Virginia passed legislation with statutory requirements for energy storage from its utilities, with legal liability if the targets are not achieved, while other states such as California and Massachusetts require reporting of implementation plans and progress (Energy Storage Association (2020), Energy Storage Goals, Targets, Mandates). Similarly, while 30 U.S. states and the District of Columbia have enacted renewable energy mandates (also known as Renewable Portfolio Standards) legally obligating utilities to achieve a targeted percentage of renewable generation, 8 U.S. states have only established voluntary renewable energy goals (NC Clean Energy Technology Center DSIRE database).

EARLY ADOPTION AND BUY-IN TO SOLAR AND WIND

As the National Renewable Energy Laboratory (NREL) notes, private and public sector investments in the industry "have enabled solar technology innovations to progress from the laboratory to the commercial marketplace." The Asian Development Bank launched the Asia Solar Energy Initiative in 2010, aiming to finance projects in Asia to "create a virtuous cycle of solar energy investments in the region, toward achieving grid parity", recognizing that the "high cost of solar technologies during the transition stage" needs to be supported by public funds and user levies.[32] Early investments in a nascent solar photovoltaic (PV) industry helped catalyze production when solar generation costs were high, and, as a result, improved unit costs and efficiencies as manufacturers overcame the learning curve. Impactful initial investments included:

- Solar power technology was adopted early on during the 1960s for power generation onboard satellites, and this investment was crucial during a time when the industry was struggling to achieve commercialization.[33]
- In 1973, the University of Delaware's Institute of Energy Conversion (IEC) built Solar One, a pioneer development that utilized solar energy for the heating and electricity needs of a residential building.[34]
- In the 1970s and 1980s, NASA Lewis Research Center, in conjunction with the U.S. Department of Energy (DOE) and the U.S. Agency for International Development (USAID), executed a number of solar PV projects around the world that demonstrated a diverse variety of use cases for solar energy.[35]
- The Carter Administration symbolically installed solar panels on the roof of the White House in 1979 in conjunction with launching a $3 billion research program for the solar industry.[36]
- NREL estimates that, between 2000–2007 (as solar entered exponential growth stages), total cumulative global public equity and private investment in solar energy (excluding government R&D funding) amounted to almost $23 billion.[37]

$23 BILLION INVESTED

in solar energy globally through public equity and private investment (excluding government R&D funding) between 2000–2007

[31] NREL (2008). A Historical Analysis of Investment in Solar Energy Technologies (2000-2007).
[32] ADB (2011). Asia Solar Energy Initiative: A Primer.
[33] U.S. DOE (n.d.). The History of Solar.
[34] U.S. Patent and Trademark Office (n.d.). A Brief History of Solar Panels.
[35] U.S. DOE and NASA (1981). Review of Stand-Alone Photovoltaic Application Projects Sponsored by U.S. DOE and U.S. Aid.
[36] Halloran, Tyler (2019). Solar Energy's Untold History and the Factors Driving its Growth Today. Fordham Journal of Corporate & Financial Law.
[37] NREL (2008). A Historical Analysis of Investment in Solar Energy Technologies (2000-2007). Note that this amount is equivalent to approximately $28 billion in 2019 when accounting for inflation since 2007.

SUSTAINED R&D INVESTMENT

Conscious investment in R&D by governments and other entities resulted in continued efficiency improvements in solar and wind technology. Long-term, stable R&D programs fostering a high level of collaboration between industry, academia, and research institutes (both public and private) were effective in reducing the price of solar PV modules, as shown in **Figure 5**.[38] For example, the DOE's Office of Energy Efficiency and Renewable Energy (EERE) R&D funding for solar and wind totaled approximately $5 billion between 2002–2021,[39] with research grants spanning universities, national laboratories, and private entities.[40]

Fig. 5

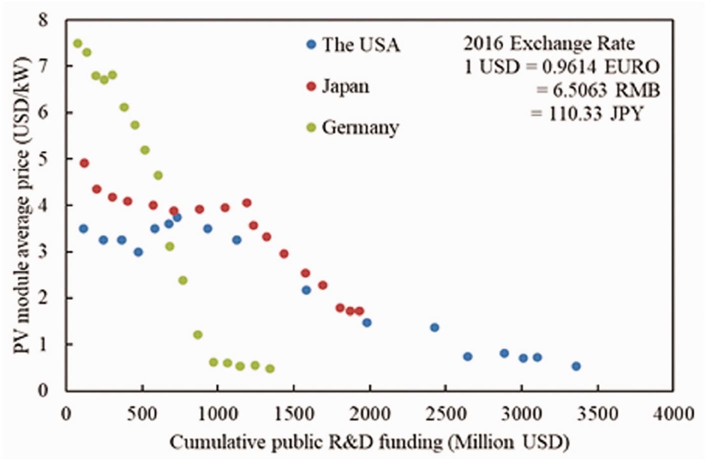


Figure 5: Average price of solar PV modules as a function of cumulative public R&D funding in the U.S., Japan, and Germany. Figure taken from Wen et al. (2020).

Globalization played a significant role in further lowering production prices — solar technology advancements achieved through R&D in developed countries (e.g., U.S., Japan, and Germany) diffused into developing countries, such as China. Those countries focused their efforts on improving production process efficiencies, and as a result, China dominates the global PV module manufacturing market with more than 70% of production.[41]

[38] Wen, D., Gao, W., Qian, F., Gu, Q., & Ren, J. (2020). Development of solar photovoltaic industry and market in China, Germany, Japan, and the United States of America using incentive policies. Energy Exploration & Exploitation, 39(5), 1429–1456. https://doi.org/10.1177/0144598720979256
[39] U.S. DOE (n.d.). Energy Efficiency & Renewable Energy Budget Search.
[40] U.S. DOE (n.d.). Solar Energy Technologies Office, Solar Energy Research Database.
[41] Wen, D., Gao, W., Qian, F., Gu, Q., & Ren, J. (2020). Development of solar photovoltaic industry and market in China, Germany, Japan, and the United States of America using incentive policies. Energy Exploration & Exploitation, 39(5), 1429–1456. https://doi.org/10.1177/0144598720979256

GOVERNMENT INCENTIVES

Government tax credits and incentive programs were critical to stimulating demand for solar projects:

- Tax credits — such as the U.S. Investment Tax Credit (ITC), which was established in the 2000s for capital investments in solar and wind — were "one of the most important federal policy mechanisms to incentivize PV development in the USA."[42]
- As seen in **Figure 6**, wind capacity additions in the U.S. are strongly correlated with the multiple expiration/renewal cycles of the federal Production Tax Credit (PTC) — increasing during years where the PTC was scheduled to expire by year-end, significantly dropping after expiry, and resuming development once reinstated.[43]
- Feed-in tariffs (FITs),[44] commonly used in China, Japan, and Germany, establish above-market prices for utilities to purchase solar and wind energy from a renewable energy generation facility, providing price stability and improving financing opportunities for such projects.[45] As shown in **Figure 7** from Wen et al. (2021), annual installed capacities of solar generation are well-correlated with the introduction or amendment of FIT policies in these countries.[46]
- Finally, consumer-level programs such as the "100,000 Roofs Programme" in Germany,[47] the "Golden Sun" program in China,[48] the "Million Solar Roof"[49] initiative and "Self-Generation Incentive Program"[50] in California, and others have made solar power accessible and affordable to the general public by providing rebates, subsidies, and favorable financing frameworks for solar installations. These programs have demonstrably stimulated demand from individual consumers.[51]

> *Tax credits were one of the most important federal policy mechanisms to incentivize PV development. Wind capacity additions in the U.S. are strongly correlated with the multiple expiration/renewal cycles of the federal PTC.*

[42] Wen, D., Gao, W., Qian, F., Gu, Q., & Ren, J. (2020). Development of solar photovoltaic industry and market in China, Germany, Japan, and the United States of America using incentive policies. Energy Exploration & Exploitation, 39(5), 1429–1456. https://doi.org/10.1177/0144598720979256
[43] U.S. DOE (2015). WindVision: A New Era for Wind Power in the United States.
[44] A FIT program typically guarantees that customers who own a FIT-eligible renewable electricity generation facility, such as a rooftop solar photovoltaic system, will receive a set price from their utility for all of the electricity they generate and provide to the grid. (U.S. EIA (2013)
[45] IRENA (2018). Renewable Energy Policies in a Time of Transition.
[46]Wen, D., Gao, W., Qian, F., Gu, Q., & Ren, J. (2020). Development of solar photovoltaic industry and market in China, Germany, Japan, and the United States of America using incentive policies. Energy Exploration & Exploitation, 39(5), 1429–1456. https://doi.org/10.1177/0144598720979256
[47] IEA (2012). 100 000 Roofs Solar Power Programme.
[48] IEA (2021). Golden Sun Programme.
[49] Environment California (2020). Three lessons from California's Million Solar Roofs milestone.
[50] CPUC (n.d.). Self-Generation Incentive Program (SGIP).
[51] It has also been suggested that renewable energy is socially contagious – that is, residential solar installations stimulate neighbors to install solar generation systems of their own (WRI, 2021).

Fig. 6

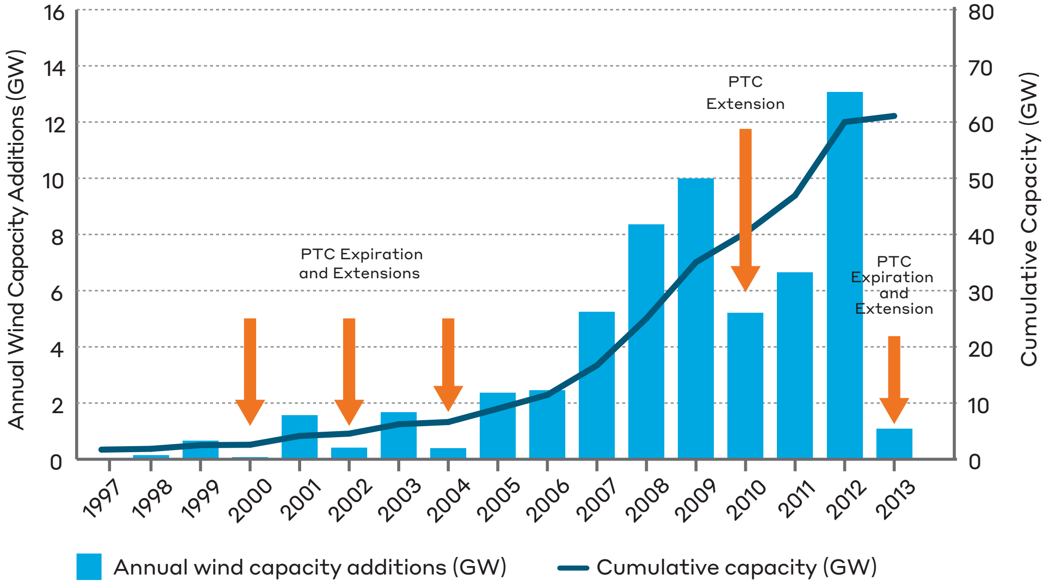


Figure 6: Annual wind power generation capacity additions in the U.S. Figure obtained from U.S. DOE (2015), WindVision: A New Era for Wind Power in the United States.

Fig. 7

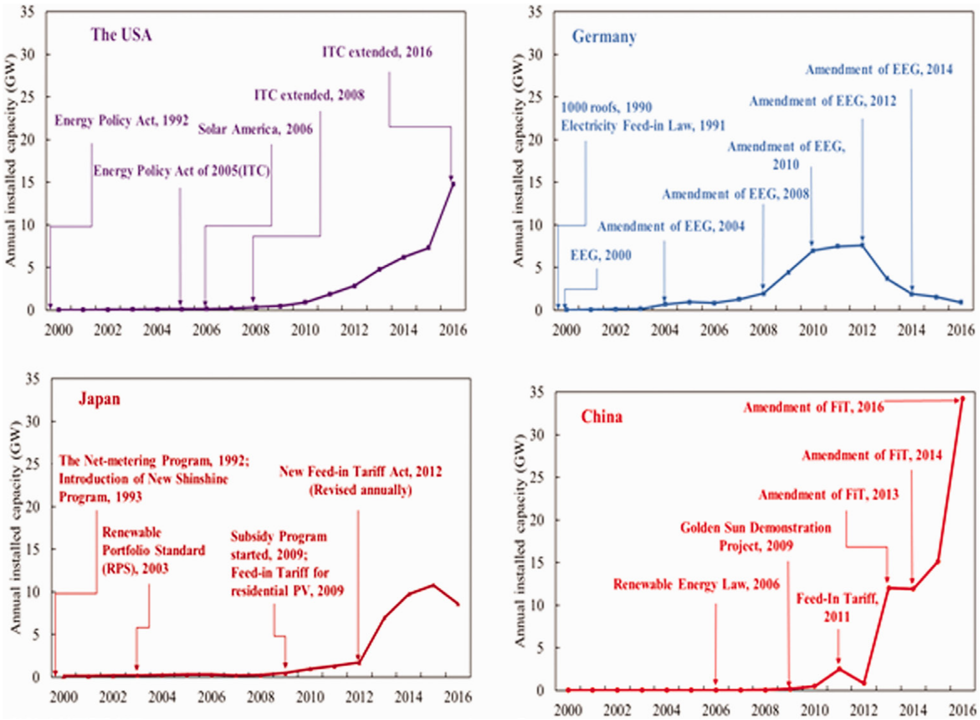


Figure 7: Annual solar PV capacity additions in relation to government investment subsidies to promote the development of solar PV deployment in the U.S., Germany, Japan, and China. FITs in Germany, Japan, and China, ITC in the U.S., and the German Renewable Energy Sources Act (EEG — a stable policy through 2010[52]) were critical to accelerating the deployment of PV generation capacity. Figure obtained from Wen et al. (2020).

> *In recent years, additional renewable energy production has exceeded mandates, and is now driven by favorable economics.*

[52] A stable German EEG policy was effective in developing PV market deployment through 2010. PV deployment slowed after 2010 following changes to the EEG, which reduced the use of FITs to control electricity prices, leading to limited market development and reduced profitability.

RENEWABLE ELECTRICITY LEGISLATIVE MANDATES AND TARGETS

In the U.S., state legislation was a key driver for the expansion of renewable electricity from solar and wind resources. State policy action not only helped create demand for renewable energy technologies through electricity quota obligations but also provided a clear market signal, making it easier to finance capital-intensive, renewable energy projects.[53] Nearly 40 U.S. states have established Renewable Portfolio Standards (RPS) or renewable energy goals, with 12 states and the District of Columbia mandating 100% renewable electricity by 2050.[54] RPS set a minimum requirement for the fraction of the state's energy to be produced from renewable resources (such as solar, wind, geothermal, biomass, and others). Approximately 50% of renewable energy capacity additions in the U.S. since 2000 are associated with state RPS targets.[55]

Globally, there are good examples of legislative targets for renewable electricity. Europe's Renewable Energy Directive (RED) set an overall renewable energy target of 20% (including electricity and transportation fuels) for its member states, and it has exceeded this target by 2 percentage points in 2020, with 37.5% of electricity produced renewably.[78] At the end of 2016, 150 countries around the world had some form of a renewable electricity generation target, with 126 of them having dedicated policies and regulations in place.[53]

Nearly 40 U.S. states have established Renewable Portfolio Standards (RPS) or renewable energy goals.

12 states and the District of Columbia have mandated 100% renewable electricity by 2050.

50% **of U.S. renewable energy capacity additions since 2000 are associated with state-level energy goals.**

Of note, renewable energy production is exceeding the mandates;[56] it is now driven by favorable economics (i.e., relative to fossil generation).[57] This can be viewed as a proof point for mandates — they can provide a clear, effective signal for investment, leading to technology maturation and ultimately economic competitiveness.

[53] IRENA (2018). Renewable Energy Policies in a Time of Transition.
[54] U.S. EIA (n.d.). Renewable energy explained.
[55] Berkeley Lab (2021). U.S. Renewables Portfolio Standards 2021 Status Update.
[56] CMUA (2022). Powering California's Future with Clean, Affordable and Reliable Energy.
[57] U.S. EIA (n.d.). Renewable energy explained.

1/40

Battery prices have dropped by more than a factor of 40 between 1991 and 2018

Lithium Ion Battery Energy Storage

Lithium-Ion (Li-Ion) battery technology is emerging as a fundamental enabler of the renewable energy revolution. Li-ion batteries power electric vehicles, help regulate the electricity grid in the face of intermittent renewable energy, and store excess renewable generation that would otherwise have been curtailed.

The evolution of battery technology and prices is very similar to that of solar and wind. The price of batteries has seen an exponential decline over recent years, having dropped by more than a factor of 40 between 1991 and 2018, with a 19% reduction for every doubling in production.[58] This cost reduction is due to the same factors that led to the growth of solar and wind: the positive feedback loop between economies of scale and innovations in battery technology.

EARLY ADOPTION AND BUY-IN BY PARALLEL REVOLUTIONARY INDUSTRIES

Initially driven by the consumer electronics market, early demand for large-scale battery energy storage technology (i.e., kilowatt/megawatt-hour capacities) was driven by growth in parallel associated industries — renewable electricity and electric vehicles.

- As solar and wind renewable power generation ramp up, batteries are emerging as an attractive solution to managing intermittency issues and time-shifting of renewable energy (i.e., storing excess solar generation produced during periods of low demand to be discharged later during peak demand), among other benefits such as grid stability.[59]
- Global electric vehicle (EV) sales are accelerating (following yet another exponential growth trajectory), having reached a 40% year-over-year increase in 2019[60] and with predictions of up to 70% of all new vehicle sales in 2040 being battery-electric vehicles.[61] In addition to creating a robust market, battery applications for EVs have led to significant R&D investments — increasing battery energy density, improving performance, and exploring novel materials.[62]

[58] Hannah Ritchie (2021). The price of batteries has declined by 97% in the last three decades.
[59] U.S. DOE (2020). Potential Benefits of High-Power, High-Capacity Batteries.
[60] IEA (2020). Global EV Outlook 2020.
[61] BloombergNEF (2021). Zero-Emission Vehicle Factbook.
[62] John Voelcker (2022). Storage Wars: What the Future Holds for EV Batteries.

SUSTAINED R&D TO ACHIEVE TECHNOLOGY AND SYSTEM-LEVEL ADVANCES

Approximately $600 million in federal R&D funding,[63] as well as various state-level R&D and commercialization programs between 2009 and 2014,[64] have enabled the successful deployment of grid-scale battery storage systems. R&D efforts have resulted in better battery technology (with Li-ion storage densities tripling in just the last decade[65]) and have improved manufacturing processes and installation/deployment efforts — specifically, engineering, procurement, and construction (EPC) activities. Together, all of that made the technology more attractive to implement, contributing to a positive feedback loop.[66,67]

GOVERNMENT INCENTIVES AND LEGISLATIVE MANDATES

Supportive government policies on battery storage have also contributed to the growth of battery storage:

- **Federal Incentives:** Battery storage projects, when coupled with solar/wind projects, are eligible for federal ITCs.
- **Regulation:** Federal Energy Regulatory Commission (FERC) has issued a number of orders in recent years enabling grid-scale energy storage providers to access energy markets,[68] providing a clear signal of market viability for prospective battery storage system providers.
- **State Legislation:** In addition to driving the growth of solar and wind energy generation via renewable energy mandates, state-level RPS goals are also being expanded to include energy storage targets.[69] These have created a robust market for energy storage, drawing interest not only from major utility companies but also from community choice aggregators (CCAs), which facilitate public access to battery storage technology.[70]

40% **Year-over-year increase reached in global EV sales in 2019, which has led to early demand for battery energy storage technology**

[63] SANDIA (2015). ARRA Energy Storage Demonstration Projects: Lessons Learned and Recommendations.
[64] Hart, David, and Sarkissian, Alfred (2016), prepared for U.S. DOE Office of Energy Policy and Systems Analysis. Deployment of Grid-Scale Batteries in the United States.
[65]Field, Kyle (2020). BloombergNEF: Lithium-Ion Battery Cell Densities Have Almost Tripled Since 2010.
[66] EPRI (2021). The State of Energy Storage: Drivers and Big Picture.
[67] NRECA (2020), Business & Technology Report. Battery Energy Storage Overview.
[68] EPRI (2021). The State of Energy Storage: Drivers and Big Picture.
[69] NRECA (2020), Business & Technology Report. Battery Energy Storage Overview.
[70] CalCCA (2020). California Community Choice Aggregators Issue Request for Long-Duration Storage RFO.

The introduction of a federal mandate for renewable fuel production in the U.S. in 2007 led to a marked increase in production of ethanol from then onwards.

Renewable Ground Transportation Fuels

Biofuel production for ground transportation — ethanol, biodiesel, and renewable diesel — grew by a factor of 60 globally between 2000 and 2020, peaking at more than 27 billion gallons in 2019 (before ethanol consumption declined slightly due to the COVID-19 pandemic).[71] As shown in **Figure 8**, ethanol and biodiesel production exceeded 18 billion gallons in 2018 in the U.S. alone, with the majority (88%) of production being ethanol.[72] In the remainder of this section, the paper takes a closer look at the U.S. biofuel industry to identify drivers that have led to its growth.

Fig. 8

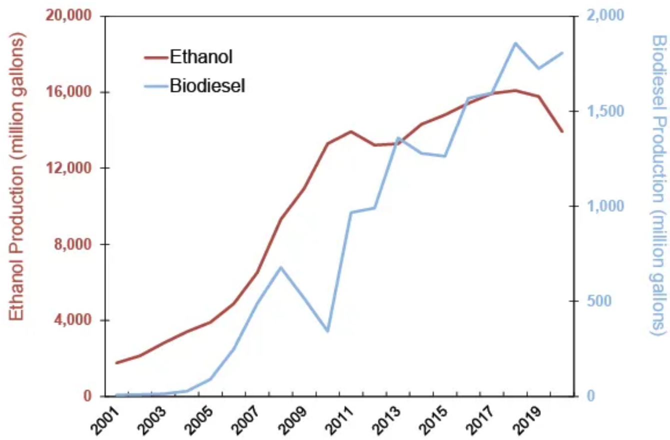


Figure 8: Ethanol and biodiesel production in the U.S. between 2001-2020. Figure taken from the Center for Sustainable Systems at the University of Michigan, Biofuels Factsheet (2021).

GOVERNMENT MANDATES FOR RENEWABLE FUELS

While biofuels have been used since the early 1900s in automotive applications, governments have more recently introduced biofuel mandates out of concern for the environment and for energy independence.

The U.S. Renewable Fuel Standard (RFS) is administered by the U.S. Environmental Protection Agency (U.S. EPA) and "requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel."[74] In 2007, the Energy Independence and Security Act (EISA) expanded the program to achieve a target of 36 billion gallons of renewable transportation fuel in the U.S. by 2022.

The U.S. EPA calculates annual renewable volume obligations (RVOs) for petroleum refiners and producers in the U.S. under the RFS. RVOs are defined for distinct categories of biofuels, including conventional biofuel from starch feedstocks (e.g., corn), biofuel from cellulosic biomass, biomass-based diesel, and advanced biofuels. Producers and refiners must meet their targets each year, either by purchasing Renewable Identification Numbers (RINs) or generating RINs by producing or importing renewable fuel. As seen in **Figure 9**, the introduction of the RFS mandates led to increased production of ethanol from 2007 onwards.

[71] BP (2021). Statistical Review of World Energy, 70th edition.
[72] U.S. EIA (2022). Monthly Energy Review, April 2022.
[73] Farm Energy (2019). History of Biodiesel.
[74] U.S. EPA (n.d.). Overview for Renewable Fuel Standard.

85x

Growth of biodiesel and renewable diesel volumes in California after the inception of the LCFS program

Fig. 9

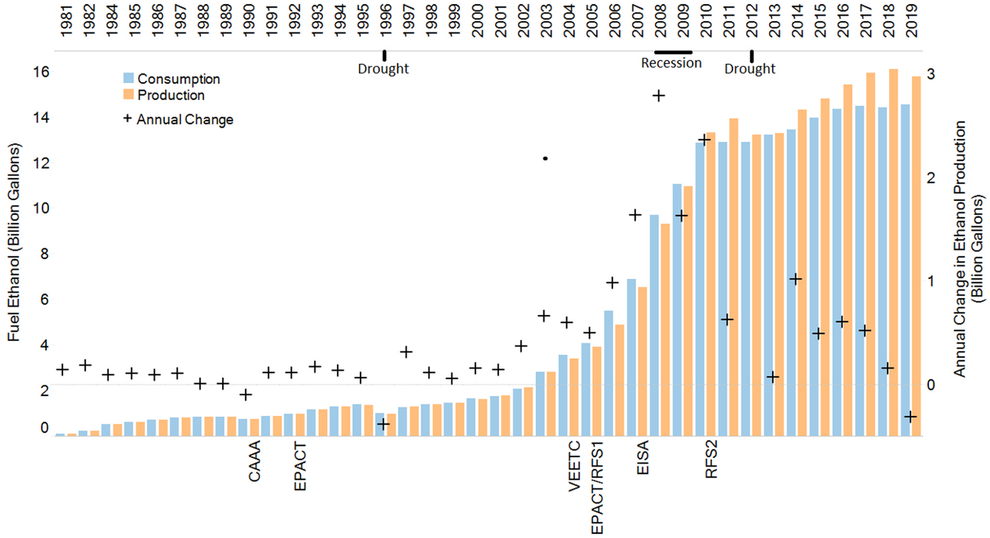


Figure 9: Ethanol production in the U.S. and key policies that accelerated growth. Figure taken from Newes et al. (2022).

In Europe, biofuel consumption is "driven almost exclusively"[75] by renewable fuel mandates such as the Renewable Energy Directive (RED and RED II)[76] and the European Green Deal (and associated proposals such as the Fit for 55 package of measures).[77] For instance, the average share of renewable energy for transportation across all EU member states increased from 1.6% in 2004 to 10.2% in 2020,[78] achieving the targets set by RED. REDII, which was adopted in 2018, increases this percentage to 14% by 2030.[79]

Low Carbon Fuel Standard (LCFS) programs have been adopted in the U.S. (California and Oregon) and Canada (British Columbia).[80] LCFS programs indirectly mandate biofuel usage by setting carbon intensity (CI) targets for transportation fuels that become more stringent over time. Fuels with CIs above the target CI generate deficits, while fuels with lower CI scores generate credits. Obligated parties are required to either acquire credits to offset their deficits or produce biofuels that carry credits.[81] LCFS programs have been effective at promoting the market for biofuels; for example, California LCFS data shows that biodiesel and renewable diesel volumes in the state have grown by more than 85 times since the program's inception in 2011.[82]

[75] USDA (2021). Biofuels Annual - European Union.
[76] European Commission (n.d.). Renewable energy directive.
[77] European Commission (n.d.). A European Green Deal.
[78] European Commission (2022). Renewable Energy Statistics.
[79] European Commission (n.d.). Renewable Energy – Recast to 2030 (RED II).
[80] The Jacobsen (2020). States with Low Carbon Fuel Standards or Considering a LCFS-Like Program.
[81] Congressional Research Service (2021). A Low Carbon Fuel Standard: In Brief.
[82] CARB (n.d.). LCFS Data Dashboard.

FINANCIAL INCENTIVES FOR RENEWABLE FUELS

Price supports for ethanol and bio/renewable diesel have been key to ensuring these fuels can successfully be commercialized and traded alongside conventional fuels.

One of the earliest policies was the Volumetric Ethanol Excise Tax Credit (VEETC), which provided a tax credit of $0.45-$0.51/gallon of ethanol between 2004-2011.[83] The Biodiesel Blenders Tax Credit provides $1/gallon of bio or renewable diesel produced (extended until 2022) and is regarded as a pivotal instrument in enabling renewable diesel production in the face of high production costs.[84] Market-based mechanisms such as the U.S. RFS and California's LCFS offer further price support for biofuels:

- For instance, the RFS value of D4 RINs (corresponding to biomass-based diesel) averaged $1.37/RIN over January 2021–March 2022.[85] At 1.6 RINs per gallon of biodiesel,[86] this results in a credit of approximately $2.20/gallon of biodiesel. Similarly, D6 RINs (corresponding to corn ethanol) provided $1.16/RIN on average during this same time period.
- Additionally, the California LCFS program provides credits of around $1.30/gallon of bio/renewable diesel.[87] The LCFS program similarly provides credits for ethanol blended into gasoline.
- The value of renewable fuels in California increased relative to fossil fuels due to additional taxes levied on petroleum products (e.g., "cap and trade" and deficits under LCFS). They currently sit at around $0.50/gallon and are predicted to reach up to approximately $2/gallon of diesel by 2030.[88]

These incentives are significant relative to current retail prices — for example, in January 2022, ethanol (E-85) sold across the U.S. at an average price of $2.97/gallon ($3.84/gallon in the West Coast), and biodiesel (B99/B100) sold at $3.96/gallon ($4.21 in the West Coast).[89] As a result of these price supports, ethanol and bio/renewable diesel prices are currently close to or even cheaper than their fossil fuel counterparts.

> *Ethanol and bio/renewable diesel prices are currently close to or even cheaper than their fossil fuel counterparts thanks to price support policies.*

[83] U.S. Department of Agriculture (2015). U.S. Ethanol: An Examination of Policy, Production, Use, Distribution, and Market Interactions.
[84] Schultz et. al. (2021). Renewable Energy Trends, Options, and Potentials for Agriculture, Forestry, and Rural America. U.S. Department of Agriculture, Office of the Chief Economist.
[85] U.S. EPA (n.d.) RIN Trades and Price Information.
[86] Ecoengineers (n.d.). An Introduction To The Renewable Fuel Standard & The RIN Credit Program.
[87] Stillwater Associates (2021). Potential Impacts of LCFS-Style Programs on Fuels Markets. Note that the specific value of credits under the LCFS program is a function of the LCFS credit value, the carbon intensity of the fuel as well as the overall program target carbon intensity.
[88] Stillwater Associates (2018). Projecting the Costs of California's Cap & Trade and Low Carbon Fuel Standard Programs.
[89] U.S. DOE (2022). Alternative Fuel Price Report (January 2022).

BLEND LIMITS AND VEHICLE/FUEL TECHNOLOGY DEVELOPMENT

As seen in **Figures 8 and 9**, ethanol production accelerated between 2005–2010 with the introduction of RFS1 before stabilizing at approximately 10% of total gasoline fuel volumes.[90] This is a result of a 15-billion-gallon limit placed by the RFS for ethanol produced from corn kernel starch, as well as a summertime ethanol blend limit of 10% in the U.S.[91] Additionally, the use of higher ethanol blends (e.g., E-85, which blends up to 83% of ethanol) requires modifications to standard internal combustion vehicles (also known as flex-fuel vehicles).

Similar blend limits for biodiesel exist between 5-20% due to fuel stability concerns. Renewable diesel, on the other hand, is a drop-in fuel of similar chemical composition to fossil diesel, and therefore not subject to blend limits. As such, growth in renewable diesel is on a stronger upward trajectory relative to biodiesel, as evident from California's LCFS quarterly sales volume data (see **Figure 10**).

Fig. 10

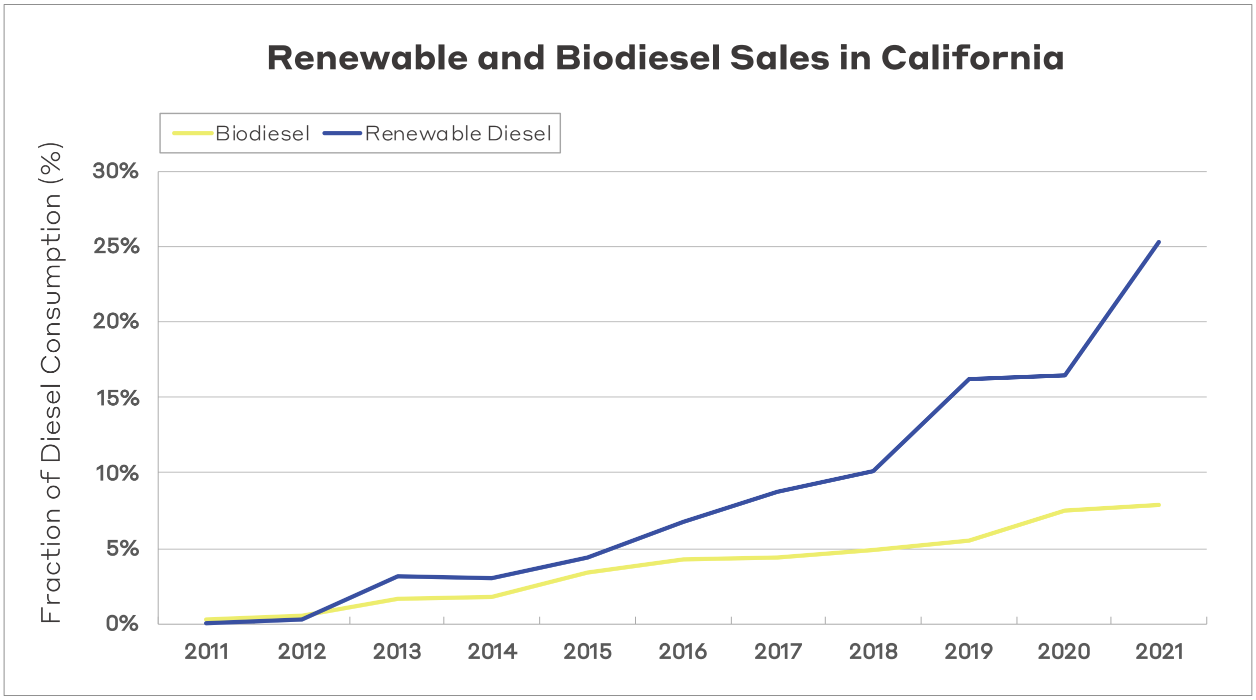


Figure 10: Proportion of diesel fuel consumed in California that is biodiesel and renewable diesel. Data obtained from California's LCFS program (LCFS Quarterly Summary Data).

[90] Per U.S. EIA, the U.S. consumed 143 billion gallons of motor gasoline in 2019.
[91] Schultz et. al. (2021). Renewable Energy Trends, Options, and Potentials for Agriculture, Forestry, and Rural America. U.S. Department of Agriculture, Office of the Chief Economist. Note that in 2022 the U.S. EPA issued a waiver to increase the ethanol blend limit to 15% (U.S. EPA (2022)).

PROVEN TRAJECTORIES AND ACTIONS THAT LED TO EXPONENTIAL GROWTH IN RENEWABLE ENERGY INDUSTRIES

Key actions taken within the solar/wind, battery, and renewable ground transportation fuel industries that led to exponential growth in those sectors.

	Renewable Energy Technology		
	Solar/Wind	**Battery**	**Renewable Ground Transportation Fuels**
EARLY ADOPTION, BUY-IN, AND INVESTMENT	Satellite applications and federal implementation projects	Growth in parallel, dependent industries	Prioritization of energy independence and energy security
GOVERNMENT INCENTIVES	Tax credits (e.g., ITC, PTC) and price supports for producers, as well as consumer incentive programs	Investment tax credits (e.g., ITC)	Financial incentives through tax credits, and RFS and LCFS programs
SUSTAINED R&D FUNDING	Public and private funding, as well as close collaboration between industry and academia	Innovation across supply chain	R&D toward drop-in fuel pathways and increased blend limits
CONSISTENT AND LONG-TERM POLICY	State-level renewable energy mandates (e.g., RPS)	Renewable energy storage targets and enabling regulations	Mandates from renewable and low carbon fuel standards (e.g., LCFS, RFS)

Enablers for Large-Scale SAF Deployment

Enablers for Large-Scale SAF Deployment

As demonstrated in the previous section, the solar, wind, battery, and renewable ground transportation fuel industries have experienced rapid scaling in production in the recent past. While some sectors such as ethanol and biodiesel have reached stable production levels (e.g., up to the approved blending limits), the solar, wind, and battery industries are on track to continue their exponential growth pattern in the coming years. Costs are also anticipated to further decline, owing to continued innovation and improvement in technology and process efficiencies.

The SAF industry is well positioned to achieve exponential scale-up in production. Currently, there are nine SAF pathways (including two co-processing pathways) approved under ASTM[92] for drop-in fuels compliant with ASTM D1655,[93] the specification prescribing characteristics for aviation turbine fuel. These processes cover a number of technologies ranging from early stage to well-established processes — including Fischer-Tropsch, hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK), synthesized iso-paraffins (SIP), alcohol-to-jet (ATJ), synthesized kerosene with aromatics (SKA), and co-processed fuels with petroleum. At present, these fuels are approved at blend limits between 5-50% with conventional fuel depending on the maturity of the technology. Furthermore, SAF is widely and unequivocally supported by national and international policymakers, aircraft and engine manufacturers, airlines, and fuel producers as the most important means by which to decarbonize the aviation sector.

Contrary to claims that feedstock limitations constrain the viability of SAF, the DOE has shown that the vast "menu" of feedstock sources currently available is more than enough to meet the projected fuel demand of the U.S. aviation industry.[94] An estimated one billion tons of feedstock material can be collected sustainably each year in the United States—sufficient to produce 50 billion-60 billion gallons of low-carbon biofuels using existing SAF technologies. This supply of feedstock is also more than enough to meet the FAA-forecasted 2050 U.S. demand of 40 billion gallons of jet fuel per year in 2050.[95] Other analysis further suggests that feedstocks are sufficient to meet global demand — SAF could power all of aviation in 2030 relying only on existing feedstocks and technologies.[96] Emerging technologies such as Power-to-Liquids (PtL) have near-unlimited SAF production potential, as they do not rely on traditional biomass-based feedstocks.[97] They instead rely on existing and proven technologies (e.g., renewable energy through solar, ATJ, and Fischer-Tropsch processes) and can take advantage of resources that would otherwise remain unused.[98]

[92] ICAO (n.d.). SAF Conversion Processes.
[93] ASTM (2021). ASTM D1655-21c: Standard Specification for Aviation Turbine Fuels.
[94] U.S. DOE (n.d.). Bioenergy Technologies Office, Sustainable Aviation Fuels.
[95] U.S. FAA (2021). United States 2021 Aviation Climate Action Plan.
[96] WEF (2020). Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation and Giulia Squadrin (2021). SAF has feedstock potential to replace jet.
[97] European Commission CORDIS (2019). Sunlight, water and CO2 – key to the jet fuel of the future.
[98] For example, solar developments on just 1–2% of global desert land (e.g., sparsely populated, nonarable acres in Chile, the Middle East, North Africa, and Australia which receive ample solar radiation) would provide enough power to produce PtL fuel to decarbonize the entire aviation sector in 2030) (WEF 2022).

While current SAF prices are reported to be between 2–5 times higher than conventional jet fuel prices,[99, 100, 101] incentive programs — including the RFS, proposed U.S. Blenders Tax Credit, and California's LCFS programs — offer some price support and are closing the gap (though, as noted below, programmatic changes are required to firmly support SAF).[103, 104]

SAF is currently only available in limited supply, with approximately 4.5 million gallons produced in the U.S. in 2020[105] and less than 70 million gallons produced globally in 2019 (accounting for less than 0.1% of global aviation fuel usage).[106] It is noteworthy, however, that SAF production has increased by a factor of approximately 20 between 2013-2015 and 2018-2020.[107, 108] Most importantly, if SAF were to scale at exponential growth rates (as demonstrated in **Figure 11**), it can address the international demand for aviation fuel with SAF in the 2030-2045 timeframe. Encouragingly, considering solely the announcements of new SAF production facilities that have been made to date,[109] SAF production is poised to exceed the growth rate seen in the solar industry.

> *Various analyses have shown that there is ample feedstock sources to satisfy global jet fuel demand - the U.S. DOE has shown that the vast "menu" of feedstock sources currently available can satisfy projected U.S. fuel demand; the World Economic Forum and Neste have substantiated that current feedstock potential can fully meet global jet fuel demand by 2030.*

[99] Cristina Brooks (2021). Sustainable aviation fuel still in short supply due to cost: IHS Markit.
[100] OAG (2022). Jet Fuel Price Pressure as SAF Levy Takes Off.
[101] Matt Kohlman (2020). As jet fuel market craters, sustainable aviation fuel prepares for takeoff.
[102] H.R.3440 - 117th Congress (2021-2022): Sustainable Skies Act, H.R.3440, 117th Cong. (2021).
[103] Fred Ghatala (2020). Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward.
[104] IATA (n.d.). Fact Sheet: EU and US policy approaches to advance SAF production.
[105] U.S. FAA (2021). Sustainable Administration Aviation Fuels (SAF) Update to FAA REDAC E&E Subcommittee.
[106] WEF (2020). Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.
[107] ICAO (2020). SAF Stocktaking, Future production Capacity.
[108] U.S. FAA (2021). Sustainable Administration Aviation Fuels (SAF) Update to FAA REDAC E&E Subcommittee.
[109] CAAFI (2020 and 2021). The State of Sustainable Aviation Fuel (SAF), and Aviation's Market Pull for SAF.

If SAF were to scale:

- At the exponential growth rates seen in solar (52%) and wind (31%), **SAF could satisfy international jet fuel demand in the 2035-2045 timeframe**.
- At an aggressive growth rate of 90%, **SAF could meet international jet fuel demand as early as 2030**.

Based on announced SAF production capacity seen in **Figure 11**, SAF production is poised to exceed the growth rate seen in the solar industry. However, **continued firm policy direction and funding commitments** are crucial to sustaining growth and **achieving exponential scale-up**.

Fig. 11

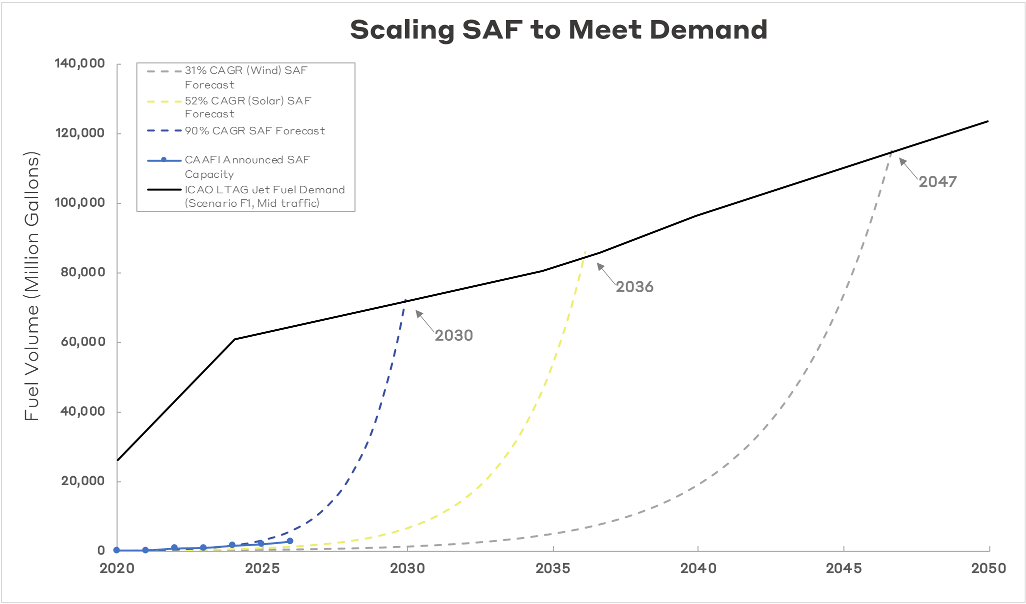


Figure 11: International jet fuel demand and projections of exponential growth trajectories of SAF based on a range of CAGRs seen in the solar and wind sectors, as well as an aspirational forecast with an optimistic growth rate. Blue dot markers indicate annual SAF production capacities that have been announced to date.

Enablers for Large-Scale SAF Deployment

20x

SAF production has increased by a factor of approximately 20 between 2013-2015 and 2018-2020

The SAF industry displays the hallmarks of early stage growth patterns seen in other renewable energy industries. Impactful initial steps have already been taken toward supporting the growth of the industry, but continued firm policy direction and funding commitments are crucial to sustaining — and accelerating — growth. Key enablers for the exponential scaling of SAF production are identified below, drawing from the policy and commercial measures enacted for other renewable energy sectors reviewed in previous sections, which have experienced exponential growth in recent years.

Key Enablers for Scaling SAF

- **Early adoption, buy-in, and investment**
- **Government incentives**
- **Sustained R&D funding**
- **Consistent, long-term policy**

2.6 billion

gallons of SAF offtake agreements were signed globally in 2021 alone

Stimulate the SAF Market Through Early Adoption and Committed Investments

Economies of scale and the ability to learn by doing were fundamental driving factors in price reductions in the solar, wind, and battery industries. Early technology adoption and buy-in was key to creating a market for those technologies, spurring competition and innovation that ultimately led to prices falling. For the SAF industry, **both commitments by end users for the purchase of SAF** (e.g., airline offtake agreements) **as well as commitments by producers for investments into SAF facilities** are key.

To date, more than 40 airlines, airports, original equipment manufacturers (OEMs), and jet fuel vendors have expressed interest in SAF procurement, with multi year offtake agreements exceeding 6.8 billion gallons of SAF. SAF offtake volumes have significantly increased in recent years. For example, in 2021 alone, more than 2.6 billion gallons of SAF offtake agreements were signed globally, with 2022 volumes expected to exceed this amount.[110]

A number of fuel producers have made commitments to making initial investments into SAF production facilities, totaling approximately 2.6 billion gallons/year of SAF production capacity by 2026 globally according to CAAFI.[111] Based on data collected from Stocktaking seminars, ICAO estimates global SAF production would reach approximately 3.5 billion gallons/year as early as 2025.[112]

[110] ICAO (n.d.). SAF Offtake Agreements.
[111] CAAFI (2021). Aviation's Market Pull for SAF.
[112] ICAO (2020). SAF Stocktaking, Future production Capacity.

Stimulate the SAF Market Through Early Adoption and Committed Investments

These offtake commitments and announced SAF production projects are commendable, and they provide a promising signal toward exponential growth of the industry. However, it is critical that these commitments and projects come to fruition. **Airlines should continue to lean in on early SAF purchase agreements. In turn, SAF producers should continue investing in new production facilities to meet this demand**. While early movers — whether end users or SAF producers — may have to contend with less-than-favorable prices, government actions on providing adequate incentives, R&D funding, and policy direction will be essential in supporting these initial efforts (as described below). Aircraft and engine manufacturers also have a role in supporting the **approval of 100% drop-in SAF** and new production pathways. Additionally, they should ensure that their products are designed to be **compatible with advanced SAF** and should **promote SAF production and use** throughout the value chain (e.g., using SAF for development and delivery, encouraging customer adoption of SAF).

Similar to initial investments into solar technology for space satellite power, **the U.S. government has a role to play in serving as an early consumer of SAF**. Following a parallel initiative by the U.S. Navy's Great Green Fleet,[113] the U.S. Air Force has an excellent opportunity to support the SAF industry by considering procurements for its jet fuel consumption (which totals approximately two billion gallons per year).[114] Taking this step would also offer the Air Force other diverse benefits including energy security, energy independence, and logistical streamlining.[115]

> While early movers — whether end users or SAF producers — may have to contend with less-than-favorable prices, government actions on providing adequate incentives, R&D funding, and policy direction will be essential in supporting these initial efforts.

[113] Launched in 2016, the Great Green Fleet has a goal of using up to a 50% blend of biodiesel for the Navy marine fleet (EESI (2016)).
[114] U.S. Air Force (2018). How the Air Force got smarter about its aviation fuel use in 2018. And Atlantic Council (2021). A clean energy agenda for the US Department of Defense.
[115] U.S. Air Force (2021). The Air Force partners with Twelve, proves it's possible to make jet fuel out of thin air.

Government Incentives Are Critical to Supporting Early Demand

Economic incentives will help achieve SAF price competitiveness relative to Jet-A, which is critical to turning offtake agreements into reality and sustaining early demand for SAF.

The Sustainable Skies Act (2021–2022) proposes a **SAF Blenders Tax Credit (BTC)**,[116] which provides a tax credit of between $1.50–$2 per gallon depending on the life cycle carbon intensity of the fuel. This program has garnered broad support from SAF producers, airlines, and nongovernmental organizations (NGOs).[117] The potential costs of the proposed BTC would constitute a small fraction of the economic impact attributable to the aviation sector, but it would enable significant reductions in greenhouse gas (GHG) emissions by making SAF more affordable. For instance, a $2/gallon credit applied to 2019 jet fuel consumption would be only 3-6% of the $0.9 trillion-1.8 trillion in annual total/direct economic activity attributable to the U.S. aviation sector in 2019.[118] As of this writing, the proposed legislation currently remains under consideration in the 117th Congress.

Further, government policies should recognize the GHG benefits of SAF relative to fossil fuels and **incentivize consumers to shift away from fossil fuel consumption** toward low-carbon SAF. This can be achieved, for instance, through a carbon tax tied to the social cost of carbon or a cap-and-trade system. According to Nobel Laureate economist Professor William Nordhaus, carbon pricing is “the single most important step to achieve climate objectives.”[119] Carbon pricing has garnered the support of over 3,600 U.S. economists, Nobel Laureates, and economic advisors as a cost-effective, equitable, and politically viable government policy to address climate change.[120]

Economic incentives will help achieve SAF price competitiveness relative to Jet-A, which is critical to turning offtake agreements into reality and sustaining early demand for SAF.

[116] H.R.3440 - 117th Congress (2021-2022): Sustainable Skies Act, H.R.3440, 117th Cong. (2021).
[117] Schneider (2021). Schneider Introduces Bill to Decarbonize Aviation, Fulfill Climate Commitments.
[118] U.S. FAA (2020 and 2021). The Economic Impact of Civil Aviation on the U.S. Economy and United States 2021 Aviation Climate Action Plan. The two percentage values reflect both direct and catalytic economic impacts attributable to the aviation sector.
[119] Prof. William Nordhaus (2021). Why Climate Policy Has Failed And How Governments Can Do Better.
[120] Climate Leadership Council (2019). Economists' Statement on Carbon Dividends.

Government-backed loan guarantees and investment/producer's tax credits for SAF facilities (e.g., the DOE Loan Programs Office's Title 17 Innovative Energy Loan Guarantee Program[121]) must be strengthened to help the bankability of SAF projects. Similar to the ITC and PTC, which facilitated solar, battery, and wind power projects, an NREL study showed that ITC and PTC would enable the SAF industry to grow successfully.[122] This study demonstrated that even after subsidies are set to expire, SAF production would continue to increase. It is therefore clear that incentive programs are needed to provide the industry with certainty to invest in producing cleaner fuels.[123]

Currently, programs such as the national RFS and LCFS programs in California and Oregon provide credit value for renewable fuels including SAF. However, these programs need to be restructured to **eliminate disincentives to SAF production** over other fuels. For example, each gallon of SAF produced via hydrotreating earns 1.6 D4 RINs, while renewable diesel earns 1.7 D4 RINs under the RFS program.[124] California's cap-and-trade and LCFS programs also contain policy provisions that reduce the value of SAF relative to renewable diesel. Coupled with additional costs of producing SAF rather than renewable diesel, these provisions disincentivize refineries from producing SAF.[125] Higher RIN multipliers have been proposed as a way to alleviate this disincentive and scale SAF.[126, 127] Further, these programs should be expanded to include incentives for advanced-biofuel, non-biogenic synthetic fuel pathways such as PtL that can deliver low or zero-carbon SAF.

Consumer-side mechanisms, such as **tax credits for consumers** of SAF (similar to those for solar/battery generation use and IRS Section 45Q, which provides tax credits for carbon capture and sequestration), would further incentivize end users to adopt SAF. Doing so in conjunction with other demand-side programs such as an **international book-and-claim system** (bridging geographic gaps between economically viable SAF production sites and demand) would make SAF more accessible and broaden the available market.[128, 129] Such systems would also help to lower feedstock costs, as SAF facilities can be built where feedstocks are more accessible (both from a geographic/logistical perspective and a price viewpoint) instead of having to be built based solely on geographical demand.

[121] U.S. DOE (2021). Loan Programs Office - How LPO Can Support the Sustainable Aviation Fuel Grand Challenge.
[122] News, E., Vimmerstedt, L., Haq, Z., and Lindauer, A. (2021). PTC and ITC for Aviation Fuel: Analysis Using the Biomass Scenario Model.
[123] Laska, Alexander. (2021). Six Reasons to Support a Blender's Tax Credit for Sustainable Aviation Fuel.
[124] McGurty, James. (2021). FEATURE: US refiners delve deeper into SAF production on policy support hopes.
[125] Fred Ghatala (2020). Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward.
[126] Neste (2019). Statement of Jeremy Baines, President, Neste US to House Energy and Commerce Committee, Subcommittee on the Environment and Climate Change Hearing on "Building a 100 Percent Clean Economy: Solutions for Planes, Trains and Everything Beyond Automobiles".
[127] Sustainable Aviation (2020). Sustainable Aviation Fuels Road-Map.
[128] A SAF book-and-claim system allows airlines to purchase SAF without being physically connected to a supply site. Producers introduce the purchased SAF into the aviation fuel supply, ultimately displacing an equivalent amount of fossil jet fuel and resulting in a reduction of the sector's overall GHG emissions. An international book-and-claim system enables SAF to be produced where it is geographically best suited, while eliminating the logistical challenges and emissions associated with delivering the fuel to a specific consumer. A credible, robust, and transparent book-and-claim system is necessary to ensure validity of SAF properties (including carbon reductions) and to avoid double-counting credits (RSB, 2021).
[129] In fact, it is noteworthy that presently a similar situation exists in the U.S. where SAF purchased by individual operators at LAX and SFO airports are comingled into the airport's fueling system and are not exclusively consumed by flights operated by those airlines (SkyNRG, n.d.)

Continued R&D Funding Is Necessary to Drive Innovation

Core to the "learning-by-doing" process is continued investment into R&D that results in higher efficiencies, innovative production processes, and novel pathways. As seen earlier, this step was crucial to achieving price reductions in solar, wind, and battery power generation. Presently, R&D institutions have been established such as the FAA's Aviation Sustainability Center (ASCENT),[130] DOE's Bioenergy Technologies Office (BETO),[131] FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program,[132] and the Commercial Aviation Alternative Fuels Initiative (CAAFI) in the U.S.,[133] as well as international programs such as the Green Plan 2030 in Singapore[134] and Green Innovation Fund in Japan,[135] which aim to advance new SAF technologies and achieve commercialization of SAF.

Further R&D is required in **SAF conversion technology improvements** to maximize the biofuel yield of a given amount of feedstock.[136] The **cost of feedstock procurement** itself has been identified as one of the most significant cost drivers for existing mature SAF pathways, and research directions have been proposed to evaluate novel collection methods to lower these costs.[137] Establishing pathways for **co-processing of SAF** in existing petroleum refineries is emerging as a means of leveraging existing refinery infrastructure and processes, thereby lowering capital costs.[138]

Dozens of other emerging low- or zero-carbon SAF technologies, including PtL[139] and advanced biomaterial-based SAF, are currently in development. These are expected to be introduced by 2030, as are non-drop-in technologies referred to as "Jet X" (which features higher energy densities and the elimination of fuel aromatics).[140] Exploring multiple technologies for low-carbon SAF increases the portfolio of pathways to develop low-carbon fuel, and it mitigates potential cost or availability issues associated with specific feedstocks. R&D efforts should also focus on **maturing the most promising of these emerging SAF technologies**.

[130] https://ascent.aero/
[131] https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office
[132] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen
[133] https://www.caafi.org/
[134] Chuarnren Chen (2022). How Singapore Is Working To Be A South East Asia SAF Hub.
[135] ArgusMedia (2021). Japan's biofuels focus pivots to SAF: USDA.
[136] U.S. DOE (2020). Bioenergies Technologies Office R&D State of Technology.
[137] U.S. DOE (2020). Bioenergies Technologies Office Sustainable Aviation Fuel - Review of Technical Pathways.
[138] Jivancic (2022). Oil Majors Look to Co-Processing as a Rapid Route to Producing Sustainable Aviation Fuels at Scale.
[139] WEF (2022). Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition.
[140] Voigt, C., Kleine, J., Sauer, D. et al. (2021). Cleaner burning aviation fuels can reduce contrail cloudiness. Commun Earth Environ 2, 114.

Continued R&D Funding Is Necessary to Drive Innovation

To be accepted for use in civil aviation, SAF is required to meet strict sustainability criteria. For instance, ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) requires SAF to meet sustainability criteria spanning life cycle emissions, global food security, ecological preservation, and other areas in order to comply with the scheme.[141] Other biofuel certification programs, such as the Roundtable on Sustainable Biomaterials (RSB), require similar criteria to be met.[142] Further R&D is needed to develop additional SAF pathways that are compliant with these **stringent sustainability requirements**.

Advances in associated sectors should inform SAF pathway development. Just as the advent of EVs and increase in renewable curtailment[143] provided the impetus for the Li-ion battery storage industry to flourish, continued reductions in renewable energy prices and expected declines in hydrogen and CO_2 production costs make PtL (or "e-fuel") pathways attractive in the coming years.[144] Renewable energy supply, which is a primary input to e-fuel pathways, is anticipated to continue to grow, with the Intergovernmental Panel on Climate Change (IPCC) concluding that the "total global technical potential for [renewable energy] is substantially higher than global energy demand".[145]

Research is required to **increase SAF blend limits** from current levels (5-50%) up to 100%. As seen historically for renewable ground transportation fuels, blend limits are a crucial limiting factor for the production of ethanol and biodiesel fuels, whereas growth in renewable diesel has outpaced other fuels given unrestricted blend limits. While neat SAF may present integration challenges due to differences in fuel composition across the various feedstocks and production processes,[146] demonstrations have proved that engines can be powered using unblended SAFs produced from HEFA and synthesized aromatic kerosene (SAK).[147]

> *R&D efforts should also focus on maturing the most promising emerging SAF technologies, such as low- or zero-carbon SAF (e.g., PtL) and advanced biomaterial-based SAF.*

[141] ICAO (2021). CORSIA Sustainability Criteria for CORSIA Eligible Fuels.
[142] RSB (n.d.). The RSB Principles.
[143] For renewable electricity generation, curtailment occurs during periods of overproduction of electricity from solar and wind resources when there is insufficient demand to consume production. For example, oversupply during the middle of the day, when the sun is brightest, is happening more frequently and at a time when demand is not at its peak. Batteries have emerged as a means to store the excess carbon-free electricity generated during periods of oversupply.
[144] WEF (2020). Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.
[145] IPCC (2011). Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[146] CAAFI (2021). 100% SAF - Highlighting and Exploring Open Questions.
[147] Will Palmer (2021). United Flies World's First Passenger Flight On 100% Sustainable Aviation Fuel Supplying One Of Its Engines, Airbus (2021). An A350 fuelled by 100% SAF just took off.

Consistent and Long-Lasting Policy Direction Is Imperative for SAF Scalability

Federal and state-level governments have had, and will continue to have, a pivotal role in enabling the transition to renewable energy. Programs with long-range goals and intermediate milestones, such as RFS and RPS, have provided clear signals for investments in renewable diesel/ethanol facilities and clean electricity generation from solar, wind, and battery storage systems. While these programs mandate a certain amount of renewable electricity or fuels, it is most important to have a consistent policy focus. For example, Germany used aspirational targets instead of mandates to grow renewable energy generation, carefully tailoring FITs to account for differences in renewable energy generation technology, scale, and location. Germany also ensured favorable treatment of "soft costs," such as financing, permitting, and grid access.[148]

Actions from local and national governments indicate a desire to support SAF development, production, and widespread use by the industry. In the U.S., the current Administration has pledged steps to enable the production of 3 billion gallons of SAF per year by 2030 and 35 billion gallons per year by 2050. The White House initiated the SAF Grand Challenge, which aims to reduce costs, enhance the sustainability, and expand the production and use of SAF through collaboration between the DOE, the U.S. Department of Transportation (U.S. DOT), the U.S. Department of Agriculture (USDA), and other agencies.[149] The proposed ReFuelEU Aviation initiative in Europe outlines proposed blending mandates — including e-fuels — for fuel suppliers beginning in 2025 and is currently in legislative process.[150]

These programs must be developed and implemented with a **holistic focus on the SAF industry**. For instance, while the SAF Grand Challenge proposes R&D workstreams to improve feedstock collection, conversion to fuels, and SAF supply chains construction,[151] it should also include: actions to implement price supports (e.g., BTC, consumer-side initiatives, etc.); improve existing renewable fuels programs to promote SAF (e.g., RFS and LCFS); and R&D funding for the emerging advanced pathways (e.g., PtL and ATJ) that are expected to be the backbone of SAF production in future.[152]

[148] Mormann, F., Reicher, D., and Hanna, V. (2017). A Tale of Three Markets: Comparing the Renewable Energy Experiences of California, Texas, and Germany.
[149] U.S. DOE (n.d.). Sustainable Aviation Fuel Grand Challenge.
[150] European Parliament (2022). ReFuelEU Aviation initiative: Sustainable aviation fuels and the fit for 55 package.
[151] U.S. FAA (2022). Sustainable Administration Aviation Fuels (SAF) Update to FAA REDAC E&E Subcommittee.
[152] SkyNRG (2022). A Market Outlook on Sustainable Aviation Fuel (May 2022).

LCFS should be expanded to other states to more widely incentivize SAF production and use. For instance, all the SAF produced in the U.S. in 2020 was consumed in California under its LCFS program.[153] LCFS programs would not only support demand by narrowing the price gap between SAF and fossil jet fuel; they would also spur innovation and competition to gradually drive the industry toward lower carbon SAF.

Finally, government action is needed to **mitigate disincentives for producing SAF** over other renewable fuels such as renewable diesel. As described earlier, existing LCFS and RFS program structures make it more favorable to produce renewable diesel over SAF, with renewable diesel being approximately 8% more valuable than SAF per gallon of fuel.[154] This leads to renewable fuel producers optimizing their product slates for renewable diesel production rather than SAF.

> *Renewable fuel programs need to be restructured to eliminate disincentives to SAF production over other fuels. Existing LCFS and RFS program structures make it more favorable to produce renewable diesel over SAF, with renewable diesel being approximately 8% more valuable than SAF per gallon of fuel.*

[153] U.S. EIA (n.d.). Biofuels explained.
[154] Stillwater Associates (2019) LCFS Price Trend and BAAQMD (2020). Sustainable Aviation Fuel: Greenhouse Gas Reductions from Bay Area Commercial Aircraft.

Consistent and Long-Lasting Policy Direction Is Imperative for SAF Scalability

Aviation emissions are difficult to abate. Unlike road transportation and stationary sources, the aviation sector does not have ready access to alternative low-carbon energy options.[155] Governments should therefore take a **cross-sectoral, holistic approach to decarbonization** — investing in supporting infrastructure to further alternative technologies where possible (e.g., expanded charging infrastructure for EVs) while supporting the development of low-carbon liquid fuels (e.g., SAF) where no other alternatives currently exist.

SCALING SAF: CALL TO ACTION

A range of actions are needed from policymakers, industry, and other SAF stakeholders to help accelerate the scale-up of SAF.

EARLY ADOPTION, BUY-IN, AND INVESTMENT

- **Airlines:** Lean in on early purchase commitments
- **Producers:** Continue investment into new SAF facilities
- **Government:** Commit to SAF purchases for military applications
- **Manufacturers:** Support the entire SAF value chain and ensure product compatibility

GOVERNMENT INCENTIVES

- Implement Blenders Tax Credit for SAF
- Incentivize SAF adoption through carbon pricing
- Provide government-backed loan guarantees and investment tax credits
- Provide competitive credits for SAF in renewable fuel programs

SUSTAINED R&D FUNDING

- Improve SAF feedstock and conversion technology, including co-processing pathways
- Mature promising low- and zero-carbon pathways (e.g., PtL)
- Increase SAF blending limits

CONSISTENT AND LONG-TERM POLICY

- Develop holistic carbon reduction policies, recognizing aviation is a hard-to-abate industry
- Expand low carbon fuel programs
- Mitigate disincentives for SAF production over other sustainable fuels

[155] ATAG (2021). Waypoint 2050 (Second Edition).

Toward Scaling SAF Deployment

The SAF industry displays hallmarks of early stage growth patterns seen in parallel renewable energy industries, and it is well poised to achieve the exponential growth seen in these renewable energy sectors. Impactful initial steps have already been taken toward supporting the growth of the industry, but continued commitment will be needed by industry and governments alike to provide the uniform and ecosystem-wide support needed to achieve scaling up of SAF. Early adoption and investment will be critical to stimulating demand in the SAF market. Government incentives are key to supporting early demand and capital investments. Continued R&D funding is necessary to drive innovation. Consistent and long-lasting policy direction is imperative for SAF scalability.

Given the scale, urgency, and imperative for carbon reductions in the aviation industry, the SAF industry must develop at scale, and this must occur well before 2050. SAF is widely and unequivocally supported by industry and policymakers as the most important means by which to decarbonize the aviation sector. Taking the learnings discussed in this paper into account, SAF is poised to be able to deliver these carbon reductions, enabling the aviation industry to play its vital role in the global economy while protecting the climate.

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