Sustainable Aviation Fuel (SAF):

A Critical Analysis, with a Focus on Agriculture, Land, and Food

A Report by the National Farmers Union

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Canada's NFU is a direct-membership national organization. Founded in 1969, and with roots going back more than a century, the NFU represents thousands of Canadian farm families, farm units, and farm workers from coast to coast, and also enjoys the support of many non-farmer Associate Members. The NFU embodies the principle that all farmers share common problems and that all farmers must come together, and work with non-farmer allies, in order to address those problems. Our organization believes that agriculture should be economically, socially, and environmentally sustainable. Food production should lead to enriched soils, clean water, a more beautiful countryside, adequate and stable farm incomes, jobs for non-farmers, thriving rural communities, healthy natural ecosystems, diverse habitats for all species, and Canadian tables arrayed with diverse, delicious, nutritious foods.

The NFU's governance structures are democratic, participatory, and progressive. A farm unit membership gives equal participation rights to all family members over the age of 14. The NFU has leadership positions for youth, women, men, and BIPOC (black, Indigenous, and people of colour) farmer representatives. It was the first major farm organization in Canada to elect a woman as President. To learn more, go to our website: www.nfu.ca .

Please join the NFU, as a farm family or farm unit, as a farm youth member, as a farm worker member, or as a non-farmer associate member. There is a place in the NFU for every person concerned about farms and food systems.

Table of Contents

Executive Summary

> "There's an underappreciation of how big the energy problem is for aviation. ... We are working at this problem and realizing it's a lot harder than we thought. We are late to the game. We are in the dark ages in terms of sustainability, compared to other sectors."
> —Phil Ansell, Director, Center for Sustainable Aviation, University of Illinois, 2024.[1]

Sustainable Aviation Fuels (SAFs) are lower-emission, non-fossil-fuel energy sources for the world's aircraft fleet—"drop-in" fuels that require no modifications to aircraft or engines. The proposal is to make SAFs largely from biological sources: corn, soybeans, and canola now and over the next decade or so, and then increasingly from straw and other "agricultural residues" and from purpose-grown energy crops such as grasses or fast-growing trees (with a minor portion from forestry residues). There is a third phase proposed: to use clean renewable energy to extract hydrogen from water and carbon from the air and combine these into a liquid fuel. But such "Electro-fuels" remain speculative and the very high costs and energy requirements suggest they may remain unfeasible.

Why should citizens and policymakers be concerned about SAFs? Because the immense scale of the global SAF project creates significant potentials to move us *away* from many of our food system, climate, decarbonization, sustainability, and social justice goals. At the same time, the huge, global SAF project may fail in its stated intent: to slash greenhouse gas (GHG) emissions and warming effects from a rapidly expanding aviation sector.

Citizens want affordable food and sustainable food systems. Farmers want to maximize soil carbon sequestration and begin to reduce emissions from fertilizer use. We all want to be able to develop renewable energy supplies that are adequate to the tasks of decarbonizing home heating, motor vehicle travel, and industry. The global SAF project risks moving us away from all these goals: it will likely raise food prices; reduce the sustainability of food systems; slow or reverse agricultural soil carbon sequestration; drive up fertilizer use and attendant agricultural GHG emissions; and put impossible-to-meet demands onto limited supplies of clean, renewable energy thereby slowing emissions reduction in other sectors.

If governments continue to encourage and subsidize the SAF megaproject, those governments risk "policy incoherence"—pursuing policies that work directly *against* the attainment of other policies and social and environmental goals. SAFs attempt to solve one problem but create many larger problems.

More important, there are reasons to question whether the SAF megaproject is even possible. Is it real? Or is it a distraction which will delay more effective emission-reduction measures and direct trillions of dollars toward the wrong investments and away from superior alternatives? Worse than a huge global project that increases food prices and on-farm emissions while solving an aviation emissions problem is a project that creates those food and farming problems while *simultaneously failing* to slash aviation emissions. That latter scenario is a significant probability. Considered within the context of planetary boundaries, limited resources and trade-offs, and the need to simultaneously solve *multiple* climate and sustainability problems—to tackle the polycrisis—the global SAF project (which includes *doubling* air travel) may simply be impossible. *At the very least*, the project raises so many questions and affects so many other parts of the economy and biosphere that every policymaker and citizen should want to learn more. The "twenty points" that follow outline why this is such a crucial issue.

1 Oliver Milman, "'Magical Thinking': Hopes for Sustainable Jet Fuel Not Realistic, Report Finds," *The Guardian*, May 14, 2024, sec. Environment, https://www.theguardian.com/environment/article/2024/may/14/sustainable-jet-fuel-report.

Twenty points to help you understand why it is important that you read this report:

1. Air travel is projected to more than double by 2050—to 22 trillion passenger-kilometres per year.[2] Boeing and Airbus plan to deliver 40,000 new aircraft by 2043. (See Chapter 2, below)

2. Globally, passenger and air freight aircraft currently consume 379 billion litres (100 billion US gallons) of fuel per year.[3] By 2050, fuel use will increase to two-thirds of a trillion litres per year (military aircraft fuels not counted, though substantial). (Ch. 2)

3. The world's airlines have pledged to reduce GHG emissions to net zero by 2050. The largest part of airlines' net-zero plan is to switch from fossil fuels to SAFs. (Battery-electric planes and hydrogen fuels are not viable large-scale options before 2050—perhaps not ever.) (Ch. 1)

4. The raw-material feedstocks for most of the SAFs will be sourced from farmland. The near-term focus is on feedstock crops such as soybeans, canola, and corn; the medium-term on agricultural residues such as straw and corn stover and on purpose-grown energy crops such as switchgrass, miscanthus, poplar, willows, etc. SAFs will shift the energy source for aviation from oil fields to farm fields. (Ch. 3, 4, and 5)

5. A thought experiment, merely to give a sense of the scale of the proposed SAF project: If all global SAFs were sourced from seeds and oilseeds (soybeans, canola, corn, etc.) and, hence, from farmland, and if all 2050 aviation fuel were SAFs, the two-thirds of a trillion litres of demand would require roughly 2 billion acres—20 times the total cropland area of Canada (5 times the cropland area of the United States). This is a thought experiment, not the plan, but it gives a sense of scale. (Ch. 3)

6. Producing even a small fraction of the huge SAFs demand from grains and oilseeds (and another larger fraction from energy crops grown on farmland) will exert upward pressure on food prices (especially as we simultaneously add two billion people to our global population). These food-price impacts will hit the poorest and hungriest hardest, but will also have negative impacts on nearly every family on Earth. SAF may come to stand for "Sacrificing Affordable Food." The SAF project will put the food-purchasing dollars of Earth's poorest billion people into competition with the vacation dollars of the richest billion. (Ch. 3 and 12)

7. In parallel, "land use change"—often a euphemism for cutting down rainforests, wilderness, and wild-animal habitat—may be extensive. GHG emissions from that deforestation and land use change are large, and though considered in SAF "life cycle analysis" (LCA) emissions estimates, we should interrogate those estimates, especially in light of the huge portion of the Earth that humans have already annexed and the immense portion of the global biomass production we are already appropriating. (Ch. 3, 7, 8, and 10)

8. The actual SAF project will be different than outlined in the corn-soy-canola thought experiment above; but will it be better? Instead of relying wholly on grains and oilseeds, airlines and fuel makers also plan to use crop residues (incl. straw and corn stover) as feedstocks. This could require hundreds-of-millions of tonnes of biomass from croplands—potentially slowing or reversing carbon sequestration and risking soil health. Another proposed feedstock is purpose-grown energy crops, which can lead to land competition and food-price impacts. (Ch. 4, 5, and 7)

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2 A passenger-kilometre is equal to moving one passenger one kilometre. Thus, a flight that moves 200 passengers 1,000 kilometres is equal to 200,000 passenger kilometres. 22 trillion passenger kilometres is equivalent to 110 million such flights.

3 This and the other figures in this Executive Summary are detailed and footnoted in the chapters that follow.

9. Partly because of the huge demands for biomass feedstocks, the airline industry is exploring production in Africa and other food-insecure parts of the world. It appears that the lands of the poor may be used to fuel the jets of the rich. (Ch. 12 and 13)

10. Many of the land-sourced SAF feedstocks targeted by the aviation industry are the same as those required for bioenergy with carbon capture and storage (BECCS). BECCS proponents say that they can produce negative-emission electricity by using carbon capture in thermal powerplants and fuelling those generating stations using forest wastes, crop residues, and energy crops—*exactly the same biomass feedstocks cited by SAF proponents*. Crop residue biomass and energy crop removals for SAFs will come atop billions of tonnes of removals for BECCS. (Ch. 4 and 8)

11. Can the planet's land surface and biosphere sustain humanity's ever-increasing demands? Here is the plan for the middle decades of this century: feed two billion additional people; produce more (land-costly) meat and dairy products for increasingly affluent households in the Global South; provide biomaterials to replace plastics; provide more cotton and other fibres for an expanding population and to replace plastic fibres; provide roughly 8 billion tonnes of biomass feedstocks annually for bioenergy with carbon capture and storage (BECCS); provide perhaps 7 billion tonnes of feedstocks annually for SAFs; generate these additional farmland-sourced food and feedstock gigatonnes even as climate impacts intensify and hit farmers harder; provide space for carbon-capturing tree-planting; do all the preceding even as we reduce fertilizer use in an attempt to reduce emissions from agriculture and return global nitrogen flows to within planetary boundaries; and do all this without expanding our agricultural or forestry land bases, in an attempt to slow the fastest extinction event in 65 million years. Policymakers and citizens must not consider SAFs in isolation, but rather within the context of the *many* other demands we plan to impose onto our biosphere and farmland. (Ch. 8)

12. SAF production will compete for scarce supplies of clean, renewable electricity, which risks slowing decarbonization in other sectors. In some airline-industry scenarios, by 2050, producing SAFs could require a quantity of electricity equivalent to half of all electricity produced globally today. Thus, SAFs may not create emissions reduction, but rather emissions *shifting*: with reductions in aviation emissions leading to slower reductions elsewhere because there is not enough clean electricity to go around. As we struggle to electrify and decarbonize automobiles, home heating, industry, etc. is it responsible public policy to add another huge demand for clean energy? (Ch. 6, 14 and 18)

13. Similarly, SAFs will create large demands for green hydrogen—with those coming atop demands for low-carbon hydrogen for fertilizer production, building heating, heavy industry, railways, ocean shipping, etc. Airline industry trade association IATA is projecting 2045 demand for green hydrogen at nearly 100 million tonnes annually. Current production of low-emission ("blue") and zero-emission ("green") hydrogen is just 1–2 million tonnes per year—implying the need for a fifty-fold scale-up, *just for aviation*. Adding aviation as a major demand for green hydrogen will slow emissions reductions in other sectors. Again, emissions shifting. (Ch. 14)

14. Net zero is <u>not</u> zero. The airlines may succeed in reducing emissions per flight and per passenger-kilometre, but they plan to double or triple the number of flights and passenger-kilometres by the 2050s, resulting in a situation wherein total emissions from the sector, in absolute terms, may be not much lower than today. To deal with this, the industry plans to use offsets and other means to reach net-zero, despite hundreds-of-millions of tonnes of actual emissions projected for 2050. Moreover, aviation is just one sector planning to fall short of actual zero emissions and make up the shortfall with offsets. The supply of credible offsets in 2050 is unlikely to meet the many large demands from multiple industries. (Ch. 16)

15. For jet aircraft, zero CO_2 emissions does not equal zero warming. Only a portion of the warming effects from aviation are caused by CO_2 emissions from burning fuel; the largest part is caused by the high-altitude cumulus clouds often visible after jets pass overhead and by nitrogen oxide effects. Even if aircraft fuels can be engineered so that they no longer add CO_2 to the atmosphere from combustion, the millions of flights annually will still drive warming as a result of non-combustion effects. Even if airlines reach their narrow net-zero CO_2 goal, as a result of doubling flight volumes, non-CO_2 effects may still drive *more* warming in 2050 than today. (Ch. 16)

16. In addition to potential food-price impacts of SAFs, there is also the issue of public subsidies. Both raise justice issues. Globally, subsidies, tax credits, and other taxpayer supports may add up to many tens of billions of dollars per year—a trillion dollars or more over the next two-and-a-half decades. But with many people struggling to afford shelter, childcare, food, or medicines, should limited government dollars be used to reduce vacation or business-travel costs? (Ch. 17)

17. SAFs present one of the largest-ever scale-up challenges. Analysts note the need for a thousand-fold increase in production and the need to complete, on average, one SAF production facility every two days between now and 2050. This will require trillions of dollars in investments. Thus, there is a good chance that airlines will fall short of their commitments. Indeed, the industry has set dozens of decarbonization goals and failed to meet almost every one. (Ch. 18 and 19)

18. The massive scale of the SAF project raises many other concerns including impacts on water availability (some SAF feedstocks will be irrigated), biodiversity losses, land access and affordability, Indigenous control of lands, land grabbing, etc.

19. For many reasons, SAFs are a farm and agricultural issue. In addition to the above, SAF production and massive demands for farm-sourced feedstocks will drive up nitrogen fertilizer use and, hence, on-farm emissions. The aviation industry's climate solution creates an agricultural emissions problem. Again, emissions shifting. (Ch. 15)

20. Superior alternatives exist (Ch. 20), including:
    a. For travel within continents and over medium distances: trains powered directly by clean, renewable electricity (which can be true zero emission and zero warming, unlike SAF-powered aviation, and which are now a mature and fully deployable technology);
    b. Demand-management measures to decrease flying (rather than doubling it by 2050) in order to moderate scale-up challenges, mitigate problems caused by competing demand for biomass and clean energy, and make over-ambitious SAF scenarios actually achievable; and
    c. Leapfrogging land-based Bio-SAFs and going directly to Electro-SAFs that do not compete for land, raise food prices, slow or reverse soil carbon sequestration, increase on-farm emissions, etc.

We are in a climate emergency which requires near-wartime-levels of action on the part of all governments and citizens. It requires rigorous, holistic, long-term thinking; hard choices; the acknowledgement of trade-offs and limits; wisdom; and bold, courageous action. No matter what the fuel source, doubling or tripling air travel by mid-century is incompatible with any responsible, science-based assessment of the challenges and trade-offs we face or the painful and damaging impacts already occurring and set to multiply in coming decades. And any plan to fuel that doubling of air travel largely from the planet's oversubscribed land base reveals an ignorance of the magnitude by which we have already transgressed planetary boundaries—how far we have already moved outside the "safe operating space for humanity" when it comes to nitrogen and phosphorus flows, land use change, species extinction, and biomass removal. (Ch. 10)

1. Introduction and SAF Primer

> "The most obvious problem is the manner in which technology is introduced to us. The first waves of description are invariably optimistic.... The information we are given describes the technologies solely in terms of their best-case use. ... Corporate and government marketers present only idealized, glamorized versions of technology, since they have no stake in the public being even dimly aware of negative potentials—the worst-case scenarios—though negative results are at least as likely to occur as positive results."
> —Gerry Mander, *In the Absence of the Sacred*, 1991.[4]

> "In the process of developing a new technology, could we proceduralize thinking through the total set of effects, not just the intended set of effects and the market benefits of those, but thinking through [the implications] if this technology really takes off, and goes to its full scale."
> —Daniel Schmachtenberger, 2024.[5]

The net zero plan for air travel

At the UN COP21 Climate Conference in Paris in 2015, the world's governments agreed to reach net zero emissions by 2050. Partly in response, in October 2021, airline industry association IATA (International Air Transport Association) approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050. The following year, the United Nations agency ICAO (International Civil Aviation Organization) adopted a similar net-zero resolution.[6] (Note that airline industry commitments regarding emissions predate, by many years, their 2021 and 2022 net-zero commitments. E.g., Canada and its airlines' 2005 agreement regarding fuel efficiency.)

The world's passenger airline and air freight corporations have limited options for decarbonization. Electric planes would require batteries too heavy for anything other than small aircraft taking short flights. This will be the case for many decades, perhaps permanently. The use of pure hydrogen (compressed or super-cooled liquid) is a possibility, but that, too, is a far-in-the-future option—requiring the complete redesign of aircraft, their engines, and global fuel-supply chains. "Both hydrogen and electric propulsion are ill-suited to long-haul flights.... Near- and long-term decarbonization hinges on SAF," writes the Canadian Council for Sustainable Aviation Fuel (C-SAF).[7]

The only option to decarbonize aviation is to find a low-emission "drop-in fuel" that is compatible with the current aircraft fleet and their engines and can be scaled up to replace fossil fuels, litre-for-litre. The answer that airlines and policymakers have fixed upon is Sustainable Aviation Fuels (SAFs).

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4 Jerry Mander, *In the Absence of the Sacred: The Failure of Technology and the Survival of the Indian Nations* (San Francisco: Sierra Club Books, 1991).

5 Nate Hagens, "The Great Simplification. Guest: Daniel Schmachtenberger: Moving from Naive to Authentic Progress: A Vision for Betterment, June 5, 2024," n.d., https://www.thegreatsimplification.com/episode/126-daniel-schmachtenberger-7; "Transcript from Nate Hagens, The Great Simplification Podcast. Guest: Daniel Schmachtenberger: Moving from Naive to Authentic Progress: A Vision for Betterment," accessed June 25, 2024, https://static1.squarespace.com/static/61d5bc2bb737636144dc55d0/t/665f7fbf34207744ae9868de/1717534656165/TGS+126+Daniel+Schmachtenberger+Transcript.pdf.

6 International Air Transport Association, "Net Zero 2050: Sustainable Aviation Fuels" (IATA, December 2023), www.iata.org/flynetzero.

7 Bentley Allan, Jonas Goldman, and Geoff Tauvette, "The C-SAF Roadmap: Building a Feedstocks-to-Fuels SAF Supply Chain in Canada" (Canadian Council for Sustainable Aviation Fuels, 2023), 59.

What are SAFs?

Sustainable Aviation Fuels (SAFs) are almost chemically identical to petroleum/fossil-fuel derived jet fuel: "Jet A." Most SAFs can be used safely now when blended up to 50 percent with conventional/petroleum jet fuel and, in the future, when used unblended.

Current aviation fuel is produced from one feedstock (crude oil) via one process (oil refining), but SAFs can be created from a wide range of feedstocks (grains, oilseeds, used cooking oils, animal tallow, agricultural or forestry residues, municipal solid waste aka "garbage" and sewage, algae, carbon and hydrogen from air and water, etc.) and by diverse chemical-industry pathways. Some SAF production feedstocks and pathways are similar to those now used to make biofuels such as renewable diesel, but others are wholly different, such as SAFs made from green hydrogen[8] that is reacted with carbon captured directly from the air. Importantly, not all SAFs are biofuels. Some are (such as those made from canola or forestry residues) but other SAFs are not (such as those made directly from hydrogen from water and carbon from the air)—these latter fuels have no biological or land-sourced inputs.

Considered over their full life cycle, many SAFs are said to produce lower GHG emissions. While conventional/petroleum Jet A fuel produces 89 grams of carbon dioxide equivalent (CO_2e) per megajoule of energy,[9] many SAFs are, according to models, projected to produce roughly half that amount, and a number are claimed to be extremely low emission, near-zero, or even negative emission.[10] According to industry models, some SAFs may be zero emission or near zero but many are *not*. *At best*, SAFs made from corn, canola, and soy *might* reduce emissions by 50 percent, compared to fossil-fuel-derived Jet A.[11] (How land-use change and soil carbon changes are handled in the Life Cycle Analysis, LCA, for such fuels is often the determining factor regarding modelled total emissions.)

Finally, some SAFs are real: in production, mature technologies, and relatively cost-competitive. Examples include corn-feedstock SAF via the Alcohol to Jet (AtJ) process/pathway. In contrast, fuels made from air and water via renewable energy remain in the R&D phase, have yet to be scaled up, and may prove so costly that they are never deployed at scale. A big part of the task of understanding SAFs is understanding what is real and what is not and what is actually feasible to be deployed in coming decades if we do, indeed, go down the SAF path. Many SAFs may prove to be no more than wishful thinking—distractions to buy time for a rapidly expanding, high-emission airline industry. For this reason, this report capitalizes "Sustainable Aviation Fuel," to indicate that it denotes, not just a set of energy sources and fuel options, but also a set of speculative plans and, potentially, a policy advocacy or public relations tool. SAF is both a descriptor and a brand.

The many varieties of SAFs

Some of us are familiar with one process for making SAFs—the method now used to make renewable diesel. Feedstocks such as canola and soy oil can be fed into the hydro-processed fatty esters and fatty

8 Grey hydrogen, the most common now, is made from fossil fuels, usually natural gas, and the resulting carbon dioxide is released into the atmosphere; Blue hydrogen is produced similarly, but the CO_2 is captured and not released; Green hydrogen is produced without GHG emissions, for example by using clean renewable electricity to split water via electrolysis into oxygen and hydrogen.

9 Air Transport Action Group, "Beginner's Guide to Sustainable Aviation Fuel," 4th Edition (Geneva: ATAG, April 2023), 2, https://aviationbenefits.org/media/168027/atag-beginners-guide-to-saf-edition-2023.pdf.

10 For the most part, this report will not delve into the tortuously complex task of unpacking and critiquing the life-cycle analysis (LCA) models and their estimates of emissions from various fuels. This report takes the position that even if one uncritically accepts the best-case versions of those SAF emission values, the SAF megaproject remains profoundly unwise—in collision with planetary boundaries. Nonetheless, the NFU remains profoundly sceptical of modelled emissions estimates, especially in light of land-use change effects. The NFU urges academics, civil servants, energy analysts, and others to dig deeply into the assumptions and processes behind LCA emissions estimates and provide a much broader range of possible LCA outcomes—beyond what may be best-case scenarios propounded by those connected to the airline and fuel industries. Most important, the NFU urges analysts to look, not at the emissions of the next litre of SAF, perhaps produced in 2025, but the last litre produced in 2050 (produced in a world struggling to feed billions more people, fuel BECCS powerplants, etc.) and consider likely land-use choices and conversions under those scenarios in those decades.

11 Kentucky Corn Growers Assoc., "A Farmers Guide to the GREET Model," KY Corn, May 9, 2024, https://kycorn.org/farmers-guide-to-greet-model/.

acids (HEFA) pathway. Post-use "waste" oils (e.g., used cooking oils) and other feedstock such as tallow can also be used in HEFA processes.

There are also existing SAF pathways and feedstocks that resemble current ethanol production. Corn (or wheat or any grain) can be transformed to alcohol and on into SAF via a process called Alcohol to Jet (AtJ).

Solid biomass such as agricultural residues (grain straw, corn stover, husks, etc.), forestry residues (twigs, branches, bark, chips, sawdust), even municipal solid waste (MSW, aka "garbage") can be converted into "syngas" and then converted to SAF via the Fischer-Tropsch (FT) process.[12]

Similarly, dedicated "energy crops" such as poplar, willow, switchgrass, and miscanthus can likewise be turned into SAF via the FT process.

Algae can provide oils as a feedstock for the HEFA process, though it is important to know that algae fuels have been discussed for decades but have yet to be scaled up or commercialized.

Finally, in this inexhaustive listing, there is a non-biomass/non-biofuel route: using renewable energy to capture carbon from the air and hydrogen from water and combining these in a process with several names: power-to-liquids (PtL); Solar-to-Jet; electro-fuels, e-fuels, or, as we name it below, Electro-SAF.

Figure 1 provides a colourful representation of how various feedstocks can be linked to various SAF production technologies. Only a subset of feedstocks and pathways are shown.

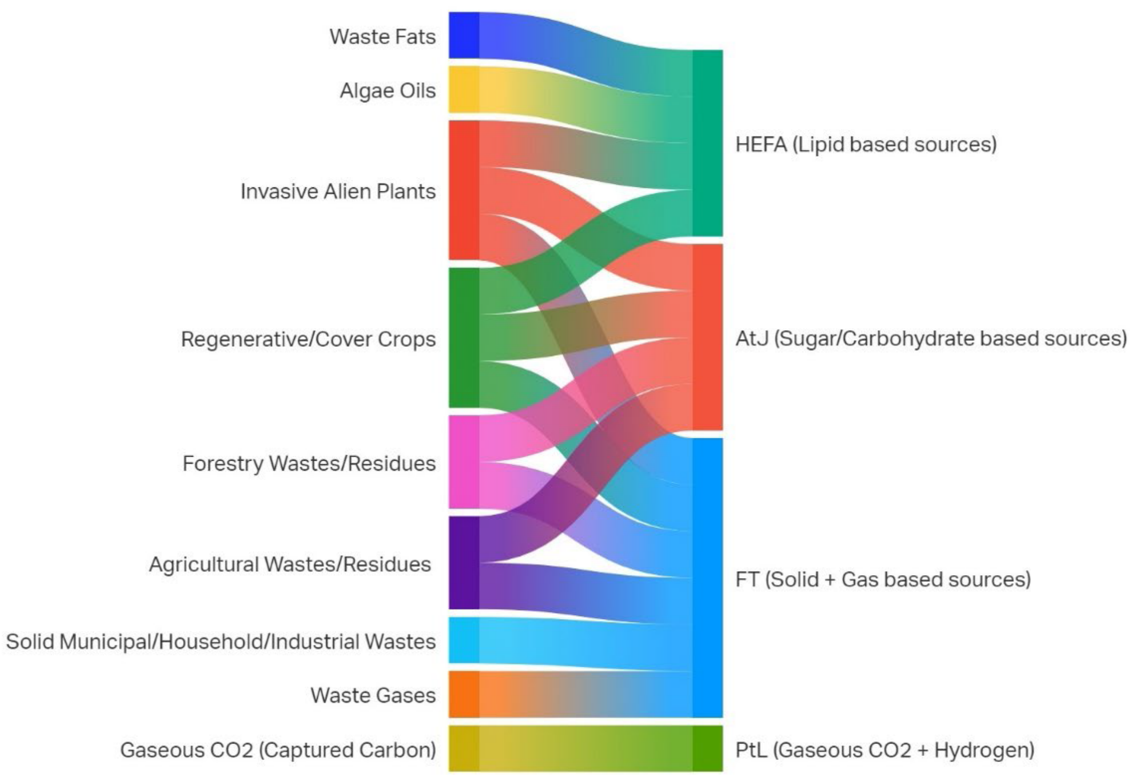

Figure 1. Some selected SAF feedstocks and associated production processes.
Note: HEFA=hydro-processed fatty esters and fatty acids (similar to the renewable diesel pathway); AtJ=Alcohol-to-Jet; FT=Fischer-Tropsch; and PtL=Power-to-Liquids, aka electro-fuels or Electro-SAF.
Source: Reproduced from International Air Transport Association, "SAF Handbook" (IATA, May 2024).

12 Those curious about the enormous challenges of turning garbage into jet fuel should study the failures of Fulcrum BioEnergy and Air Products and Chemicals: https://cen.acs.org/energy/Fulcrum-BioEnergy-abandons-trashfuel-plant/102/web/2024/06

With seven or eight approved production pathways and (depending on how you subdivide them) many dozens of feedstocks, there are a lot of combinations for SAF production. This is complicated chemistry. To simplify, in this report we divide SAFs into four main classes and focus on these:

1. Bio-SAF {seeds}: SAF from corn, soy, canola, and other grains and oilseeds produced using processes similar to current biofuels.

2. Bio-SAF {residues}: "more advanced" biofuels from agricultural straw, forest residues, and other biomass—the long-awaited "cellulosic" fuels.

3. Bio-SAF {energy crops}: purpose-grown energy crops—trees, grasses, and other plants—that maximize biomass production (these, too, are cellulosic fuels).

4. Electro-SAF (aka Power-to-Liquids, PtL): non-biofuels that utilize processes that turn clean renewable electricity, water (a source of hydrogen), and air (a source of carbon) into liquid hydrocarbon jet fuel.

In this report, we will use these four categories: Bio-SAF {seeds}; Bio-SAF {residues}; Bio-SAF {energy crops}; and Electro-SAF. Other SAF feedstock/process combinations exist, but these four encompass the majority of probable SAF tonnage, and are the ones of most interest to farmers. (The final one, Electro-SAF, does not entail the use of biomass or farmland, but it is of interest to farmers because an assessment of its viability is crucial to determining just how much SAF will be made from bio-/land-sourced feedstocks. Unless Electro-SAF can be rapidly scaled up and reduced in cost, bio-/land-sourced feedstocks will have to supply almost all the two-thirds-of-a-trillion litres of fuel needed each year by mid-century.)

It is likely that SAF processes and feedstocks will be developed in a certain order—in stages. Bio-SAF {seeds} may play a significant part in the early stage. Indeed, processes and feedstocks now used to produce automotive ethanol, biodiesel, and renewable diesel may be expanded and/or redeployed toward SAFs. There are limits, however, as these first-stage fuels trigger impacts and concerns, including:

- land-use change and associated emissions (e.g., diverting canola or soy tonnage to biofuels in one country can spur farmland expansion and subsequent forest clearance in another, releasing carbon from soils and reducing biodiversity);

- reducing food supplies or increasing demand for crops and, thus, driving food-price increases;

- driving up fertilizer use and attendant agricultural GHG emissions; and

- limits on feedstock availability.

(Some types of stage-one SAFs, however, may not trigger these problems, such as SAFs made from used cooking oil. This feedstock, however, is very limited and may be little more than a distraction.[13])

Industry associations IATA (International Air Transport Association), ATAG (Air Transport Action Group), and ICAO (United Nations International Civil Aviation Organization) and virtually all airlines acknowledge these limits and impacts and are clear that only a minor portion of total SAF supplies can come from Bio-

13 Ryanair CEO Michael O'Leary stated bluntly: "You want everybody running around collecting fucking cooking oil? *There isn't enough cooking oil in the world to power more than one day's aviation*," [italics added]. Gwyn Topham, "Ryanair's Michael O'Leary: 'There Isn't Enough Cooking Oil in the World to Power One Day of Green Aviation,'" *The Guardian*, December 26, 2023, sec. Business, https://www.theguardian.com/business/2023/dec/26/ryanairs-michael-oleary-there-isnt-enough-cooking-oil-in-the-world-to-power-one-day-of-green-aviation .

SAF {seeds}. Also note that stage-one Bio-SAF {seeds} are far from zero-emission. Canola, corn, soy, and other grain and oilseed feedstocks produce significant emission from on-farm fuel and fertilizer use, land use change, etc.

Because most stage-one Bio-SAF {seeds} fuels have these many limitations and defects, airlines and other proponents point to stage-two fuels made from agricultural or forest residues or purpose-grown energy crops: Bio-SAF {residues} and Bio-SAF {energy crops}.

Stage-three fuels, Electro-SAFs, are not biofuels, have no biomass inputs, are not land-sourced, and, theoretically, have no feedstock limits. The message from airlines and their industry associations is that after an initial reliance on stage one fuels and then stage two, as we move closer to 2050, airlines will diversify SAF supplies and rely more on zero-emission stage-three Electro-SAFs. But there are many reasons to critically evaluate such predictions, and to instead adopt the more conservative view that SAFs will be primarily land-source fuels, with the impacts and limitations that entails. Chapter 3 through 6 provide more detail on SAF stages, feedstocks, processes, and probable costs.

2. SAF Demand

> "2010 global production of biofuels was 20 million tonnes per year [25 billion litres]. That's expected to *explode* with the advent of new fuel mandates. If those mandates are met, we have something like 100 million tonnes [125 billion litres] of biofuels that we're looking at supplying" [italics added].
> —Aaron Hanson, Global Data, 2024.[14]

> "In 2052, global passenger traffic is expected to reach close to 25 billion, approximately 2.5 times the 2024 projection."
> —Airports Council International, Advisory Bulletin, 2024.[15]

> "Airbus and Boeing expect that manufacturers will deliver more than 40,000 new commercial aircraft over the next 20 years."
> —Cathy Buyck, *Aviation International News*, 2023.[16]

> "Demand for jet fuel [is] expected to more than double by 2050 and triple by 2070...."
> —US Department of Energy, National Renewable Energy Laboratory, 2024.[17]

Above, this report gave an introduction to SAF *supplies*: feedstocks and production pathways. Here, we look at *demand*: assessing the quantities of SAFs that may be required in coming decades.

Key to understanding the likely future trajectory of SAF production and feedstock demand is to understand the expansion plans of airlines. A revenue passenger-kilometer (RPK) is a unit used to measure air travel. As we might expect, it means moving one paying passenger one kilometer. In 2019, the global airline industry delivered travel equal to 8.7 trillion passenger-kilometres.[18] COVID-19 slashed travel, for a time, but numbers have now rebounded such that IATA projects 2024 air-travel volume at 9.1 trillion revenue passenger-kilometers.[19]

Most important for our analysis is where the airline industry sees itself going. Most projections are for a two-and-a-half-fold increase by 2050—increasing to about 22 trillion passenger-kilometres per year.[20] Figure 2 shows the past, present, and projected future of global air travel.

14 Don Norman, "Feed Markets and the 'Big Oil Deficit,'" *Manitoba Co-operator*, May 30, 2024.

15 Airports Council International, "Advisory Bulletin," February 13, 2024, https://aci.aero/2024/02/13/the-trusted-source-for-air-travel-demand-updates/.

16 Cathy Buyck, "Airbus and Boeing Tout Demand for More Than 40,000 New Aircraft," *Aviation International News*, June 18, 2023, https://www.ainonline.com/aviation-news/air-transport/2023-06-18/airbus-boeing-raise-20-year-forecasts-aircraft-deliveries.

17 R. Gary Grim et al., "The Challenge Ahead: A Critical Perspective on Meeting U.S. Growth Targets for Sustainable Aviation Fuel," March 26, 2024, 1, https://doi.org/10.2172/2331423.

18 International Air Transport Association, "Global Outlook for Air Transport: A Local Sweet Spot" (IATA, December 2023), 17, https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---december-2023---report/.

19 International Air Transport Association, "Global Outlook for Air Transport: Deep Change" (Montreal: IATA, June 2024), 16, https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport-june-2024-report/.

20 International Air Transport Association et al., "Aviation Net-Zero CO2 Transition Pathways: Comparative Review" (IATA, April 2024), tbl. 3, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/nz-roadmaps.pdf.

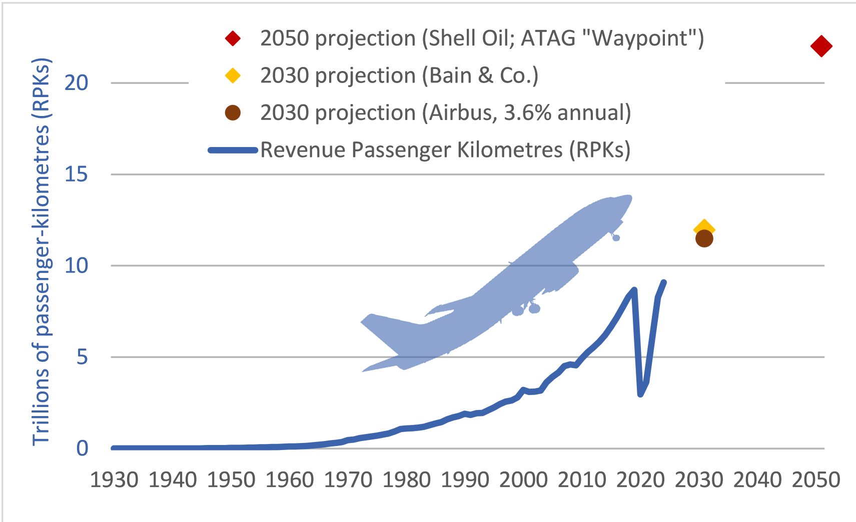

Figure 2. Air travel, passenger-kilometers, global, 1930–2023, with 2024, 2030, and 2050 projections.
Sources: Airlines for America; International Air Transport Association (IATA); Bain & Company; Air Transport Action Group (ATAG); Airbus; Shell Oil.[21]

Note that it took many decades for air travel to reach 5 trillion passenger-kms per year—it took until 2010; we are on track to add to that total another 5 trillion passenger-kms per year by 2026 (just 16 years later); and the next 5 trillion passenger-kms per year added by 2038 (12 years later); and another 5 trillion per year by 2047 (9 years later).

As demand for flying grows, so, too, will demand for fuels. The projection is for a rise from 375 billion litres (99 billion US gallons) of fossil fuel in 2024[22] to 640 billion litres (512 million tonnes or about 169 billion US gallons) of predominantly SAFs in 2050.[23] By 2050 or soon after, SAF demand may be two-thirds of a trillion litres per year.[24]

21 Airlines for America, "World Airlines Traffic and Capacity," Traffic and Operations: 1929-Present, accessed January 22, 2023, https://www.airlines.org/dataset/world-airlines-traffic-and-capacity/; Bain & Company, "Air Travel Forecast to 2030: The Recovery and the Carbon Challenge," Bain, March 27, 2024, https://www.bain.com/insights/air-travel-forecast-interactive/; Air Transport Action Group (ATAG), "Waypoint 2050: Summary Report," Second Edition, September 2021, https://aviationbenefits.org/media/167418/w2050_v2021_27sept_summary.pdf; International Air Transport Association, "Global Outlook for Air Transport" (Montreal: IATA, 2023), https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---december-2023---report/; Shell Oil and Deloitte, "Decarbonising Aviation: Cleared for Take-Off" (Shell, 2021), https://www.shell.com/sustainability/our-climate-target/reducing-emissions-from-transport-and-industry/_jcr_content/root/main/section_1553918000/slider/promo_copy_42179059_.multi.stream/1667916442677/e4f516f8d0b02333f1459e60dc4ff7fd1650f51c/decarbonising-aviation-industry-report-cleared-for-take-off.pdf; Airbus, "Global Market Forecast 2023" (Toulouse, June 13, 2023), https://www.airbus.com/sites/g/files/jlcbta136/files/2023-06/GMF%202023-2042%20Presentation_0.pdf.

22 International Air Transport Association, "Industry Statistics: Fact Sheet" (IATA, December 2023), https://www.iata.org/en/iata-repository/pressroom/fact-sheets/industry-statistics/.

23 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap" (Montreal: IATA, September 2024), 11, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/finance-net-zero-roadmap.pdf; See also: International Air Transport Association, "Net Zero 2050: Sustainable Aviation Fuels," 4; Air Transport Action Group (ATAG), "Waypoint 2050: Summary Report"; International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 4; Johnathan Holladay, Zia Abdullah, and Joshua Heyne, "Sustainable Aviation Fuel: Review of Technical Pathways" (Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2020), https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

24 This estimate for passenger aviation and air freight does not include military aircraft, which burn tens-of-billions of litres per year.

3. Bio-SAF {seeds}: Canola, Soybeans, Corn, and Farmland

> "Mark my words: [for] the next 20 years, farmers are going to be providing 95 percent of all the sustainable airline fuel."
> —US President Joe Biden, July 28, 2023.[25]
>
> "In feedstocks, Canada has opportunities across all SAF pathways. In the short-run, commercial volumes will be dominated by HEFA-based SAF from oilseeds. ... Canola will produce the balance of early volumes."
> —The Canadian Council for Sustainable Aviation Fuel (C-SAF), 2023.[26]
>
> "Today in Manitoba, the Honourable Jonathan Wilkinson, Minister of Energy and Natural Resources, joined the Honourable Wab Kinew, Premier of Manitoba, to announce a new combined federal investment of $6.2 million in [Azure Sustainable Fuels Corp.] to support the future of sustainable aviation fuels in Manitoba.... Azure's planned processing facility will ... [produce] around one billion litres of sustainable aviation fuel annually, primarily from Canadian feedstock such as canola and soybean oils."
> —Government of Canada news release, 2024.[27]
>
> "Expanded use of commodity vegetable oils including soybean and canola could play a role in growing SAF volumes."
> —USDA, US EPA, US DOT, US DOE, 2022.[28]
>
> "If just one-quarter of the world's aviation fuel likely needed in 2050 were to come from vegetable oil, its production would need to double globally."
> —World Resources Institute, 2024.[29]
>
> "Today, nearly 40 percent of America's corn crop is turned into ethanol, up from 10 percent in the mid-2000s."
> —*New York Times,* 2023.[30]

SAF is a farming issue. It is a land issue. It is an agricultural policy issue. Because SAF will increase demand for grains and oilseeds, it is a food-price issue. Because it will drive up fertilizer use, it is an agricultural emissions issue. Despite speculation about entropy-reversing fuels made from air and water and powered by renewable electricity, for the next couple decades, at least, most feedstocks will be taken from the biosphere, and most of that from farmland. Figure 3 shows a projection of Canada's most promising biogenic and waste feedstocks. Note three categories: "oilseeds," "ag residue," and "ethanol": feedstocks in the first two of those categories will come wholly from farmland and the third mostly from that land.

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25 The White House, "Remarks by President Biden on Helping Workers and Innovators Invent and Make More in America | Auburn, ME," The White House, July 29, 2023, https://www.whitehouse.gov/briefing-room/speeches-remarks/2023/07/28/remarks-by-president-biden-on-helping-workers-and-innovators-invent-and-make-more-in-america-auburn-me/.

26 Allan, Goldman, and Tauvette, "The C-SAF Roadmap: Building a Feedstocks-to-Fuels SAF Supply Chain in Canada," 9 & 27.

27 Natural Resources Canada, "Minister Wilkinson Announces Over $6 Million to Unlock Sustainable Aviation Fuel Production in Manitoba," news releases, January 17, 2024, https://www.canada.ca/en/natural-resources-canada/news/2024/01/minister-wilkinson-announces-over-6-million-to-unlock-sustainable-aviation-fuel-production-in-manitoba.html.

28 U.S. Department of Energy et al., "SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel" (Washington, D.C.: DOE, DOT, USDA, EPA, September 2022), 17, https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

29 Dan Lashof and Audrey Denvir, "Under New Guidance, 'Sustainable' Aviation Fuel in the US Could Be Anything But," September 5, 2024, https://www.wri.org/insights/us-sustainable-aviation-fuel-emissions-impacts.

30 Max Bearak, Dionne Searcey, and Mira Rojanasakul, "Airlines Race Toward a Future of Powering Their Jets with Corn," *The New York Times*, November 30, 2023, https://www.nytimes.com/interactive/2023/11/30/climate/airlines-jet-fuel-ethanol-corn.html.

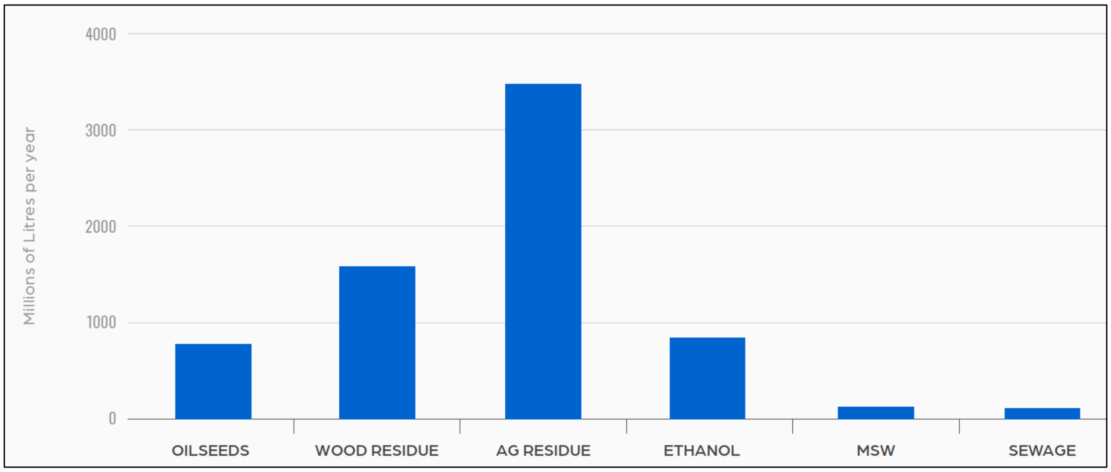

Figure 3. Most promsing Canadian SAF feedstock from biogenic and waste sources.
Source: Reprinted from Canadian Council on Sustainable Aviation Fuel (C-SAF), "The C-SAF Roadmap...," 2023.[31]

A thought experiment (merely to give an idea of the massive scale of the global SAF proposal): How much land would be required worldwide if the aviation sector was fuelled 100 percent by SAFs in 2050 and all those SAFs were produced from oilseeds such as canola and soybeans? As a rough rule of thumb, each tonne of canola or soybean feedstock can produce about 300 litres of SAF (more for canola, less for soybeans). (See Appendix 3 for multiple estimates, sources, and assumptions.) In Canada, each acre yields roughly a tonne of canola or soybeans (more for soybeans and less for canola). Using these two approximations, we can compute that producing the 640 billion litres per year of SAFs projected for 2050 would require about 2.1 billion acres of cropland (and more if SAF output from distillate was not maximized).[32] Canada has just under 100 million acres of cropland. Hypothetically, *to produce all 2050 SAFs from oilseeds might take an area equal to 21 times Canada's total cropland area* (more than 5 times the US cropland area).

Granted, some of the world's agricultural areas produce higher yields than Canada, so the hypothetical global area needed might be only 15 times the Canadian cropland area, or just 12 times—maybe just 4 times the cropland area of the US rather than 5. On the other hand, the preceding calculations grant a high SAF-yield-from-distillate[33] so the hypothetical global cropland area needed could be higher if a lower SAF fraction is assumed.

This report acknowledges that no one is proposing that the entire 2050 aviation fuel supply—two-thirds of a trillion litres—be produced solely from canola and soybeans. Clearly, that is impossible. Airlines and their industry associations acknowledge this and are forthright that only a portion of SAFs can be produced from such crops. Nonetheless, this thought experiment reveals the magnitude of the proposed SAF project and the challenges and impacts it will create—*impacts that will remain large even if only a fraction of SAFs come from field crops*.

Clearly impossible from soybeans and canola, we should ask: is it any more feasible if we add in agricultural residues and energy crops grown on farmland? We will explore that question below, in Chapters 4 and 5.

31 Allan, Goldman, and Tauvette, "The C-SAF Roadmap: Building a Feedstocks-to-Fuels SAF Supply Chain in Canada," 45.

32 One tonne of canola or soybeans per acre times 300 litres of SAF per tonne equals 300 litres per acre. 640 billion litres of projected 2050 demand divided by 300 litres per acre equals 2.1 billion acres.

33 When a bio-refinery produces SAF, it also produces other fuels (with longer or shorter carbon chains). A given tonnage of feedstock (e.g., corn, canola, straw, or switchgrass) produces a certain tonnage of "distillate"—the industry term to encompass the various fuel outputs, including SAF, renewable diesel, and gasoline-like fuels. Only a portion of the distillate is SAF, and the size of that portion is under the control of the plant operator. There is a trade-off: maximize the SAF percentage and the bio-refinery sacrifices output of total liquid fuels. Maximize overall output and the SAF fraction falls. SAF fractions run from 20 percent to 70 percent of distillate, depending on operator choices. See International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 19 & 16; International Air Transport Association, "SAF Handbook" (IATA, May 2024), 16, https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-handbook.pdf.

4. Bio-SAF {residues}: Spinning Straw into Gold

> "To meet longer-term (2050) targets, the aforementioned feedstocks will be joined by ... agricultural residuals (e.g., corn stover, cover crops, and livestock manure).... 2050 SAF goals cannot be reached without the use of agricultural residues such as corn stover...."
> —USDA, US EPA, US DOT, US DOE, "SAF Grand Challenge Roadmap," 2022.[34]

The initial phase of SAF production will be fed largely from grains and oilseeds; the second phase will rely on non-food feedstocks such as agricultural residues. Figure 3, above, shows the medium-term projection for Canadian feedstocks: ag residues make up more than half. The plan is to source many millions of tonnes of straw, corn stover, and other biomass residues from Canadian farm fields, and many times that amount globally.[35]

Several concerns arise from the plan to remove straw, stover, and other plant material. First, soil carbon is built up and maintained partly by crop residue inputs. Canada's National Inventory Report (NIR)—our official calculations and reporting of GHG emissions and soil carbon changes—notes that soil carbon gains are a function of "the change in crop productivity/*crop residue C input* to soils based on yield estimates" [italics added].[36] Soil carbon levels are, to a significant extent, a direct function of the crop residue carbon inputs going into the soil—a direct function of the amount of residue left on the land. Simply stated, soil carbon sequestration is largely determined by the *balance* between two factors: carbon input, largely from crop biomass, and carbon release, largely from bacterial decomposition/oxidation of soil carbon. When C inputs exceed C releases, soils gain carbon, and when releases (or removals) exceed inputs, soils lose.

Crop residue removals may have *large* impacts on soil carbon levels. For example, sequestration on Canadian cropland averaged 20 million tonnes per year in the decade preceding 2021, but a 2021 drought changed that situation; reduced production of crop biomass caused the balance to shift. In 2022, as a result of the 2021 drought, soil carbon flows switched from 20 million tonnes of sequestration to a *release* of nearly 20 million tonnes. Soils released or <u>de</u>sequestered carbon as CO_2 emissions as a result of below-normal levels of crop residues being returned to the soils. Figure 4 shows that large 2021-'22 swing.

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34 U.S. Department of Energy et al., "SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel," 12 & 30.

35 Are not crop residues now often burnt? In Canada, no. Residue burning is mostly confined to flax acres. AAFC notes that "burning is no longer a common practice in Canada..." and that "the practice of burning straw has declined dramatically due to environmental concerns and improvements in the ability of field machinery to till and plant in heavy residue." See Clearwater and Hoppe, Environmental sustainability of Canadian agriculture: Agri-environmental indicator report series – Report #4, AAFC, 2016, https://publications.gc.ca/collections/collection_2016/aac-aafc/A22-201-2016-eng.pdf . The Canadian situation is largely reproduced in the US. Globally, about 6% of residue is burnt. See Smerald, Rahimi, and Scheer, "A global dataset for the production and usage of cereal residues in the period 1997–2021," Scientific Data 10:685 (2023), https://pmc.ncbi.nlm.nih.gov/articles/PMC10562449/pdf/41597_2023_Article_2587.pdf

36 "National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada," Part 1, Canada's Submission to the United Nations Framework Convention on Climate Change (UNFCC) (Ottawa: ECCC, April 2022), 187.

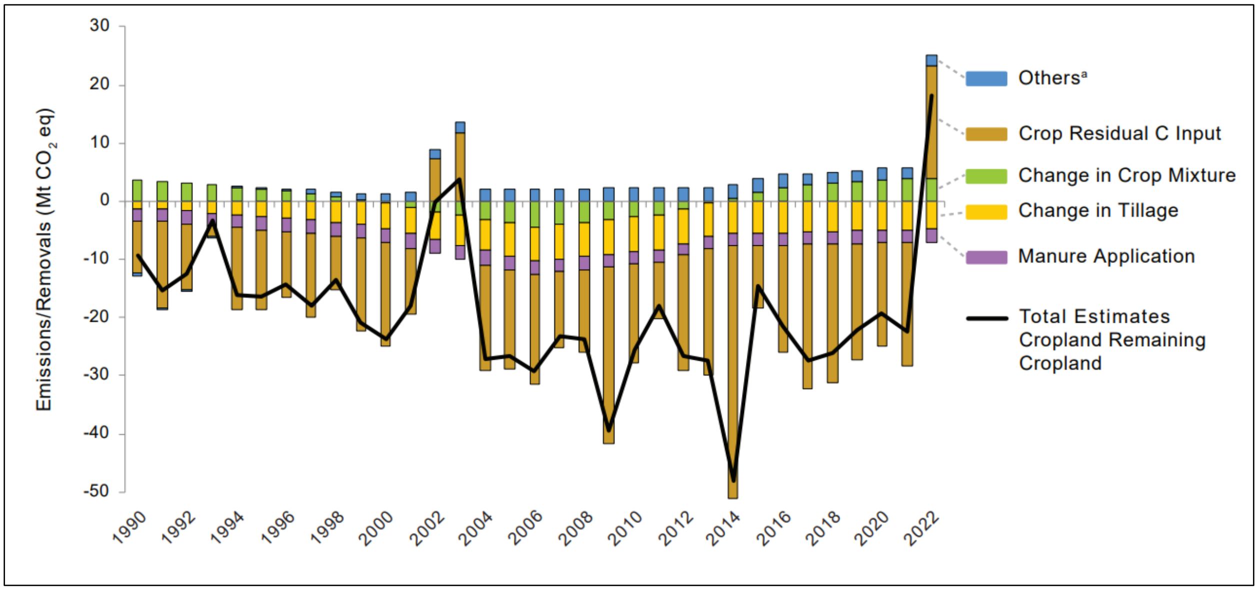

Figure 4. Canadian cropland soil carbon flows: sequestration and emissions, 1990–2022.
Source: Reprinted from ECCC, NIR, 2024.[37]

Note from the graph that the switch from soils gaining carbon to soils releasing carbon was driven wholly by a change in one factor: Crop Residual C Input (see the long, tan bar in the graph above). Less crop biomass residue on the land tipped the balance from soil carbon gain to soil carbon loss. This is an important point: a perhaps 30 to 50 percent reduction in biomass input as a result of low rainfall did not reduce sequestration rates by 30 to 50 percent—rather, it reduced sequestration rates by *more than 100 percent*—driving sequestration rates below zero and up into release/desequestration territory. A reduction of biomass left on fields did not slow sequestration, it reversed it. And even if biomass removal will not, in every case, cause soil carbon losses, it will almost certainly reduce rates of gain. Soil carbon gains are crucial means of improving soil health and the water-holding capacities of soils, thereby increasing climate change resilience.

The airline industry acknowledges these potential negative effects noting that "There are worries about soil health impacts if too much residue is removed from fields."[38]

Before we invest trillions of dollars globally in fuel systems that will remove billions of tonnes of straw, corn stover, and other biomass annually, we should precisely quantify effects on farmland soil carbon and soil health.

In addition to the negative effects of biomass removal on soil carbon levels, those levels will also be adversely affected by warming. Earth is on track to warm 2.6–3.1 degrees Celsius this century.[39] The Canadian Prairies are warming at twice the global average rate and are projected to continue doing so.[40] Thus, 80+ percent of Canadian farmland is on track for 5 or 6 degrees C of warming this century. We know from scientific studies that warmer temperatures can cause carbon losses because, as soils warm, micro-organisms can become more numerous and more active and break down and release soil carbon faster. One study reports that "nearly all models of global climate change predict a loss of carbon from

37 Environment and Climate Change Canada, "National Inventory Report 1990-2022: Greenhouse Gas Sources and Sinks in Canada, Part 1" (Ottawa: ECCC, 2024), 200, https://publications.gc.ca/collections/collection_2024/eccc/En81-4-2022-1-eng.pdf.

38 SimpliFlying and Sustainable Aviation Futures, "Pathways to Sustainable Aviation Fuel: North American Edition" (SimpliFlying, 2024), 30.

39 United Nations Environment Programme, "Emissions Gap Report 2024" (Nairobi: UNEP, 2024), https://www.unep.org/resources/emissions-gap-report-2024.

40 F. Warren and D. Lemmen, Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation (Ottawa: Government of Canada, 2014), 6, http://epe.lac-bac.gc.ca/100/201/301/weekly_checklist/2014/internet/w14-26-U-E.html/collections/collection_2014/rncan-nrcan/M174-2-2014-eng.pdf . This high rate of warming is not unexpected: continental interiors and higher latitudes warm much faster than the global average rate.

soils as a result of global warming...."[41] Thus, even without residue removal, warming will make it difficult to maintain soil carbon levels and sequestration rates. Residue removal will compound that difficulty.

Beyond soil carbon impacts are effects on fertility and nutrients. Every tonne of straw or stover removed will take from the field, in addition to carbon, smaller quantities of nitrogen, phosphorus, potassium, and micronutrients.[42] A portion of these quantities will have to be replaced, requiring additional chemical fertilizer tonnage.

Removing straw and other residues increases the risk of wind and water erosion. And less straw on the surface can increase evaporation and moisture loss, hurting yields and reducing climate resilience.

Given the many negative impacts of residue removal, the quantities needed will be of interest. One indicator is the US Department of Energy's *Billion-Ton Report* published in 2024. That report projects agricultural residue availability in the United States at 183 million US tons (166 million tonnes) per year, mainly corn stover with a contribution from wheat straw.[43]

The US DOE's *Billion-Ton Report* implies an annual residue removal rate of about 1.6 tonnes per acre of corn stover (144 million tonnes ÷ 90 million acres of corn) and 0.4 tonnes per acre for wheat straw (16.3 million tonnes ÷ 40 million acres of wheat).

Important to understand, however, is that these per-acre numbers are idealized averages. In the real world, market forces and transportation logistics will not lead to uniform removals across all acres, but rather very uneven draws of crop residues, with land close to SAF bio-refineries pushed to provide high levels and land far away tapped for less or none. Transporting biomass is costly; thus, the net price received by the farmer will vary inversely with distance creating the very clear market signal to draw heaviest from the land that is closest.

Millions of acres to bale and millions of tonnes to truck

Any ag-residue-based SAF production stream will require huge amounts of labour, materials, fuel, machinery, transportation, logistics coordination, etc. Farmers, already working flat-out during the grain harvest, would somehow have to collect and compact ("bale") residues over much of their land—over tens-of-millions of acres in Canada, perhaps a hundred-million acres in the US, and across billions of acres globally. That process would require energy (and farm machinery that is energy-intensive to produce). The relatively bulky baled residues would have to be loaded and trucked to numerous plants spread across the landscape (or to hub-and-spoke collection sites where they may be further compacted or pyrolyzed to prepare them for further transport to SAF production facilities). The exact details of the collection and transport processes are not important because all scenarios reveal the need for huge quantities of time, labour, material, and energy and the creation of enormous logistics challenges.

Important to understand, though this report focuses on fuels for aviation, many of the points made here will apply to any sector that intends to draw massively on biomass for fuels or materials. The concerns raised here apply equally to any potential biofuels megaprojects for ocean shipping, railways, or heavy trucking. They apply, very specifically, to bio-energy with carbon capture and storage (BECCS) which also plans to draw heavily on biomass from farmland (see Ch. 5 & 8). And this report's concerns apply *especially* to the *concurrent* demands from *several* such sectors and megaprojects. Though we focus on SAFs, citizens and policymakers are urged to think more broadly about all bio-based "solutions."

41 William Schlesinger and Jeffrey Andrews, "Soil Respiration and the Global Carbon Cycle," *Biogeochemistry* 48, no. 1 (January 2000): 11.
42 Kevin Gould, "Corn Stover Harvesting" (Michgan State University, 2007), https://www.canr.msu.edu/uploads/236/58572/CornStoverHarvesting.pdf.
43 U.S. Department of Energy and M. H. Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources" (Oak Ridge, TN: U.S. DOE, Oak Ridge National Laboratory, March 2024), 99.

5. Bio-SAF {energy crops}: Wood-Burning Jet Planes?

> "By growing biomass crops for SAF production, American farmers can earn more money during the off seasons by providing feedstocks to this new market...."
> —*Ontario Grain Farmer* magazine, 2022.[44]
>
> "Agricultural lands are the greatest single source of biomass production potential explored in this report. By ... integrating about 9% of [US] agricultural land into purpose-grown energy crop production, agricultural lands can provide about ... *398* ... million [US] tons of cellulosic biomass per year...."
> —US Department of Energy, *Billion-Ton Report*, 2024.[45]

Purpose-grown energy crops include woody or grassy/herbaceous crops that are fast growing and high-yielding. Examples of grassy/herbaceous energy crops include switchgrass and miscanthus. Examples of woody energy crops include willow and poplar, often coppiced: grown to a medium height and then cut low in order to spur rapid and bushy regrowth. These "cellulosic" feedstocks are then turned into jet fuel via the Fischer-Tropsch (FT) or Alcohol to Jet (AtJ) SAF pathways.

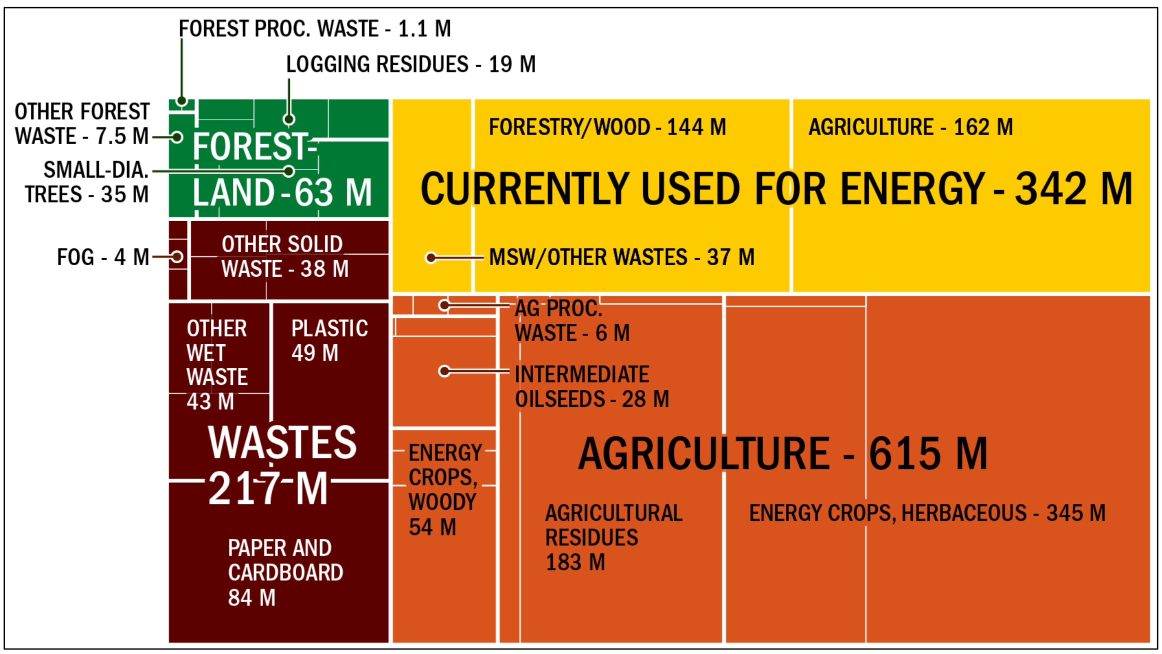

Figure 5. US biomass resources (in the mature-market medium scenario), millions of dry US tons per year.
Source: US DOE, *Billion-Ton Report*, 2024.[46]

Figure 5 shows that biomass-based SAFs will probably come mainly from farmland—in the US, North America, and likely globally. Note the small green rectangle in the upper left: US forest residues are projected to provide perhaps 63 million US tons (57 million tonnes) of feedstocks per year, but US agriculture is projected to provide nearly ten times as much: 615 million US tons (558 million tonnes). Agricultural residues (straw, corn stover, etc.) contribute 183 million tons per year—three times more than forest residues. But the largest biomass feedstock source is projected to be energy crops grown on

44 Owen Roberts, "Turning the Friendly Skies Green," *Ontario Grain Farmer*, May 2022, 6, https://www.google.com/search?q=turning+the+friendly+skies+green&oq=turning+the+friendly+skies+green&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIHCAEQIRigATIHCAIQIRigATIHCAMQIRigAdIBCDY2NzFqMGo3qAIAsAIA&sourceid=chrome&ie=UTF-8.

45 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," 121.

46 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," xxiii.

farmland, contributing about 400 million US tons (363 million tonnes) per year. While this is a US analysis, the general outlines are probably applicable globally.

Unlike some analyst organizations, which try to make the case that energy crops will be grown on unused, marginal, abandoned, or degraded land,[47] the US Department of Energy is more realistic. The DOE says that "allocating purpose-grown energy crop production to tracts of low-yielding lands in isolation of economic interactions would fail to reflect realistic futures and inevitable economic interactions among crop markets."[48] The DOE goes on to project that energy crops in the US will be grown "on 8%–11% of agricultural land"[49] and quantifies this as the conversion of 26 million acres of US cropland and 50 million acres of pastureland from food production to energy crops.[50]

A question arises: would this conversion of 8–11% of US farmland be replicated around the world? If so, what could be the effects as we simultaneously expand other demands on farmlands? To put this another way, as we add billions more people to our planetary population, and as we do so amid intensifying climate impacts on food production, are we confident that 10 percent of our farmland is surplus to need?

Below, in Chapter 7, we return to this questionable idea that there exists large areas of unused or surplus land that are available for energy-crop cultivation.

Another issue for energy crops is scale-up challenges. Currently, in the US, energy crop production and utilization is essentially zero[51]—suggesting that the economics and on-farm returns of these crops may be disappointing. And not only will there be a scale-up challenge to get farmers to plant and harvest tens of millions of acres of these crops, there will be a parallel problem in scaling up collection and processing of these hundreds of millions of tonnes, in the US, and billions of tonnes globally. All of this will require massive adjustments and investments on-farm and in processing—on-farm investments and changes that are unlikely if farmers continue to make good returns on traditional crops.

Déjet vu

Readers who have been following the biofuels debate over the past couple decades will read the preceding about SAFs from agricultural residue and energy crops and recall the long-touted "cellulosic ethanol"—biofuels made from cellulose in wood and straw rather than from starches in corn or wheat.

Despite years of "coming soon," cellulosic ethanol has failed to debut. In a 2022 article in *Physics Today*, entitled "Whatever Happened to Cellulosic Ethanol?" author David Kramer notes that "Despite a decade and a half of big US federal investments in R&D and in pilot and demonstration plants, ethanol from noncrop biomass has yet to become a commercial reality in the US."[52]

From some perspectives, in the past, it seems that the promise of cellulosic ethanol was deployed to blunt objections to the land-use and food-price impacts of corn, soy, and canola biofuels—to defuse the "food vs fuel debate." There is good reason to question whether we should today pin our hopes for low-emission air travel on these long-promised and long-delayed fuels.

47 International Air Transport Association, "SAF Handbook," 15.
48 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," 101.
49 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," xxiii.
50 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," xxviii.
51 U.S. Department of Energy and Langholtz, "2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources," 34.
52 David Kramer, "Whatever Happened to Cellulosic Ethanol?," *Physics Today* 75, no. 7 (July 1, 2022): 22–24, https://doi.org/10.1063/PT.3.5036.

How much biomass feedstock globally?

Very briefly, just how much agricultural biomass—crop residues plus energy crops—might SAFs demand? Here is an approximation:

Table 1. Back-calculation from litres of SAF in 2050 to tonnes of biomass feedstock potentially needed.

Descriptor	Value	Unit	Source
SAF needed in 2050	640,000,000,000	Litres/year	See above
Conversion factor for litres of fuel to tonnes	1,250	Litres/tonne	https://aviationbenefits.org/media/167233/fact-sheet_13_saf-metrics-and-conversions_4.pdf
SAF needed in 2050	512,000,000	Tonnes/year	By calculation. See also IATA, "Finance: Net Zero CO_2 Emissions Roadmap," 2024, p. 11.
SAF fraction from distillate	0.5	SAF/distillate	IATA, Finance: Net Zero CO_2 Emissions Roadmap, Sept. 2024, Table 2.
Distillate needed to yield SAF needed	1,024,000,000	Tonnes/year	By calc'n. Note that distillate is split 50%/50% into SAF & other products (incl. renewable diesel)
Tonnes of distillate per tonne of feedstock	0.14	Distillate/feedstock	IATA, Finance: Net Zero CO_2 Emissions Roadmap, Sept. 2024, Table 2.
Tonnes of biomass needed	**7,314,000,000**	Tonnes/year	By calculation

Table 1 shows that the biomass needed in 2050 could be approximately 7.3 billion tonnes per year.[53] Feedstocks such as corn, soy, and canola are limited. Used cooking oil, even more so.[54] On the other hand, there is no clear indication whether Electro-SAFs will ever be a viable reality; IATA projects them to remain about three-times more expensive than fossil fuel Jet A, even past 2050.[55] Thus, it may remain the case that most of the feedstocks will need to come from biomass, and most of that from farm fields.

But there's more....

Bio-SAF *plus* BECCS

The 7 billion tonnes annually of biomass calculated above would come atop other demands for biomass, with the largest probably coming from bioenergy with carbon capture and storage (BECCS) when that technology is deployed at massive scale, as is planned.

BECCS and other "negative emissions technologies" (NETs) are built into most of the United Nation's Intergovernmental Panel on Climate Change (UN IPCC) scenarios that project future temperatures below 2.0 degrees of warming.[56] To explain: Given current and probable future levels of GHG emissions, most IPCC scenarios assume we will overshoot safe GHG concentrations in the medium-term (2040s, '50s, '60s, etc.) and then later have to draw back those GHGs from the atmosphere and sequester them in the ground or oceans. Thus, though seldom voiced, BECCS and other NETs are a big part of most governments' plans to keep our biosphere stable and habitable—they are *assumed* in future projections that keep warming within tolerable limits. Most important, *BECCS systems would draw on exactly the same biomass supplies as SAFs: crop and forest residues, purpose-grown energy crops, etc*.

53 This will yield 640 billion litres of SAF and an equal volume of non-SAF biofuels based on an assumed 50 percent SAF-from-distillate fraction. The 7.3 billion tonnes of biomass per year will create about 640 billion litres of SAF per year and an equal quantity of non-SAF fuels such as renewable diesel.

54 See footnote 13

55 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 23.

56 Pete Smith et al., "Biophysical and Economic Limits to Negative CO2 Emissions," *Nature Climate Change* 6, no. 1 (January 2016): 42, https://doi.org/10.1038/nclimate2870.

Scientists estimate that the quantity of BECCS (or other NETs) needed to be deployed in the second half of this century is equivalent to the removal of 3.3 billion tonnes of carbon per year.[57] Agricultural straw is roughly 40 percent carbon and energy crops would have a comparable carbon content, if slightly higher. So, assuming 100 percent carbon capture at BECCS plants (real-world performance will be much lower), to sequester 3.3 billion tonnes of carbon, if all was provided from agricultural feedstocks, the requirement would be 8.3 billion tonnes of biomass annually. This tonnage for BECCS added to the 7.3 billion tonnes annually for SAFs equals 15.6 billion tonnes per year.[58]

Total global farmland area, cropland and grazing land, is just under 12 billion acres. Of course, most of that will be fully subscribed feeding our soon-to-be-10-billion-person global population. Even if we could find a spare couple billion acres (which is more than twenty times the cropland area of Canada), we'd have to extract more than seven tonnes of biomass per acre, every year, year after year. (For context, this represents about double the harvestable per-acre tonnage of corn stover[59] and a large multiple of the harvestable per-acre tonnage of wheat straw.)

Also to consider, many of the Earth's acres are already contributing straw and other biomass: for livestock bedding, garden mulching, heating and cooking fuels, construction materials such as thatch or mud-brick making, paper and packaging materials, etc.

Finally, when thinking about our limited supplies of crop residues, energy crops, and other biomass, we should consider that not all uses are equal in their benefits. As with SAFs, there are many problems with BECCS, but leaving aside those problems for the moment, it is useful to compare the benefits of channeling our limited biomass to BECCS rather than SAFs. BECCS is GHG net-negative, whereas SAFs, considered in aggregate, are not even GHG neutral, but rather a net source of emissions and, as we will see below, a major source of non-emission-related warming effects. Again, BECCS has its own problems, but putting those aside, we should consider this question: for the largest climate benefits, if there exist sustainably harvestable agricultural biomass supplies, should we direct those limited residue streams to BECCS or SAFs? The answer seems clear: BECCS provides negative emissions, whereas SAFs do not. Further, the electricity from BECCS provides a broad benefit to most citizens, while SAF-powered flying is only for the few. (See Ch. 12 re the small percentage who fly.)

Moreover, aviation can use Electro-SAFs to wholly eliminate its need for biomass, whereas BECCS cannot. This is one reason why the SAF project should leapfrog its biomass "transition" phase and go straight to Electro-SAFs. The best course is to refrain from building a costly, unsustainable, feedstock-limited, and soon-to-be-obsolesced biomass-based SAF production system and instead invest those trillions of dollars into Electro-SAF facilities.

Academics conclude:

> "The scaling up of SAF to not only maintain but grow global aviation is problematic as it competes for land needed for nature-based carbon removal, clean energy that could more effectively decarbonise other sectors, and captured CO_2 to be stored permanently. As such, SAF production undermines global goals of limiting warming to 1.5°C; a conflict that is neither recognised in the roadmaps nor in the public debate."[60]

57 Smith et al., "Biophysical and Economic Limits to Negative CO2 Emissions," 43.

58 This report struggles with the fact that not all sources list whether their calculations and coefficients are based on dry straw or stover or straw or stover with moisture levels normal at the time of collection and baling—often 10 to 25 percent. Thus, all figures here should be taken as ±20 percent. Future versions of this report can tackle this dry vs not-dry issue. That said, the final refinement of these values will have no effect on the overall conclusions and analysis of this report.

59 Gould, "Corn Stover Harvesting."

60 Susanne Becken, Brendan Mackey, and David S. Lee, "Implications of Preferential Access to Land and Clean Energy for Sustainable Aviation Fuels," *Science of The Total Environment* 886 (August 15, 2023): 2, https://doi.org/10.1016/j.scitotenv.2023.163883.

6. Electro-SAFs: Liquifying Electricity

"E-fuels made from hydrogen and captured carbon dioxide (CO_2) via the power-to-liquids (PtL) process can boast extremely low emissions compared to the fossil fuels they replace, depending on the source of carbon. Moreover, e-fuels don't face the same challenges as biofuels regarding the availability and sustainability of biomass feedstock. As a result, hard-to-abate transport sectors like shipping and aviation are looking to e-fuels to help them decarbonize. The PtL pathway is set to expand rapidly throughout the 2020s, from a handful of pilot plants in 2024 to a potential global capacity of over one billion gallons per year in 2030."
—Bloomberg New Energy Finance, "Power-to-Liquids Primer: Fuel from Thin Air," 2024.[61]

"Third-generation SAF or synthetic fuels represent the cutting edge of SAF technology. This category includes fuels synthesised using renewable electricity, also known as Power-to-Liquid (PtL) or e-fuels. ... While theoretically promising, the practical challenges of integrating green hydrogen and captured CO_2 into jet fuel production at scale are formidable. The aviation industry's tight margins further complicate adoption of potentially costlier fuels."
—Simpliflying, "Pathways to Sustainable Aviation Fuel...," 2024.[62]

This report uses the term "Electro-SAF" to refer to drop-in jet fuels made from air (a source of carbon, C) and water (a source of hydrogen, H) all powered by renewable electricity. That same process is variously called power to liquids (PtL), solar-to-jet, air-to-fuel, sun-to-liquids, electrofuels, and e-fuels. Figure 6 shows a simplified diagram of the process. Figure 7 shows a similar process in more detail. The CO_2 for such processes can be taken from the air (direct air capture, or DAC) or from the exhaust of an industrial or energy-producing source, such as an ethanol refinery.

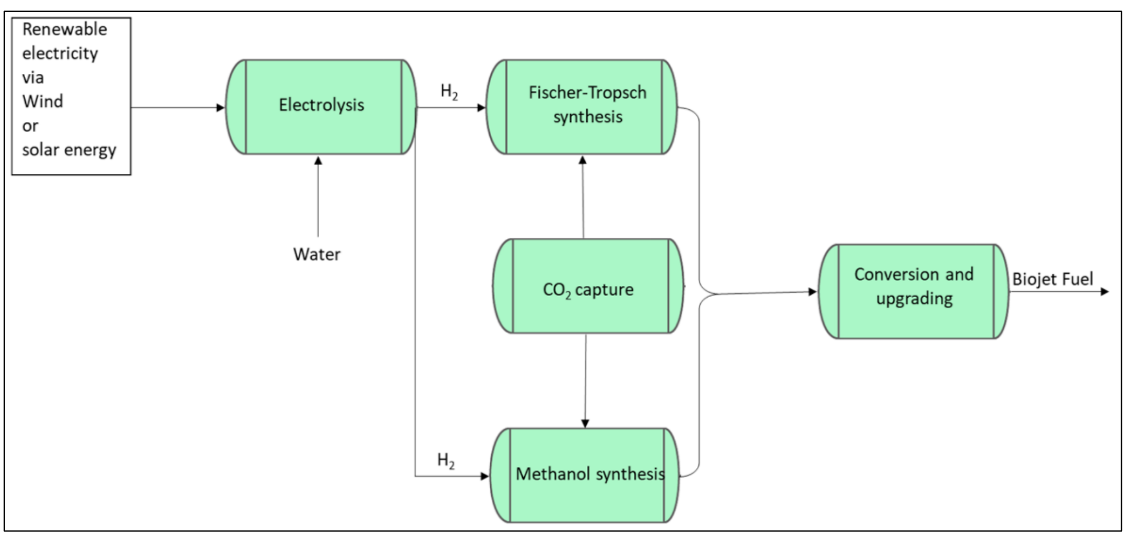

Figure 6. Simplified schematic of Electro-SAF production from renewable electricity, electrolyzed hydrogen, and captured CO_2.
Source: Reproduced from Peters et al., 2023.[63]

61 Rose Oates, "Power-to-Liquids Primer: Fuel From Thin Air," *BloombergNEF* (blog), May 7, 2024, https://about.bnef.com/blog/power-to-liquids-primer-fuel-from-thin-air/.

62 SimpliFlying, "Pathways to Sustainable Aviation Fuel: APAC Edition" (Sustainable Aviation Futures, 2024), 17–18.

63 Morenike Ajike Peters, Carine Tondo Alves, and Jude Azubuike Onwudili, "A Review of Current and Emerging Production Technologies for Biomass-Derived Sustainable Aviation Fuels," *Energies* 16, no. 16 (January 2023): fig. 10, https://doi.org/10.3390/en16166100.

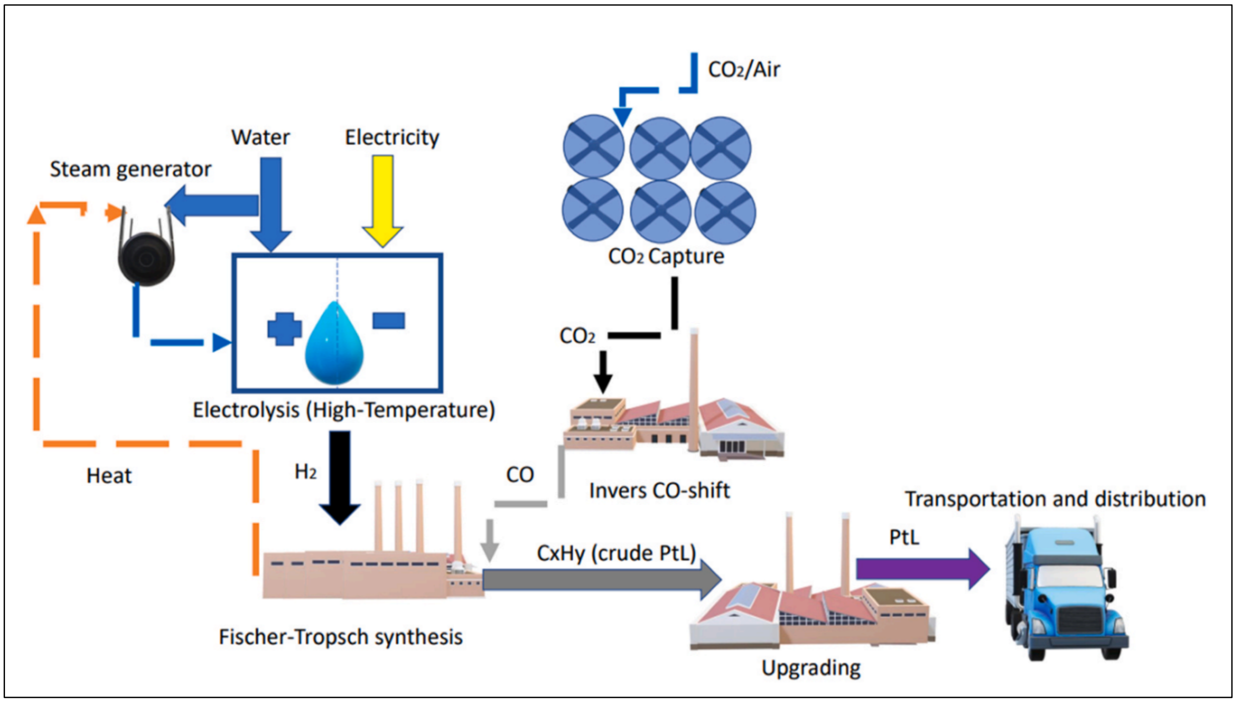

Figure 7. Electro-SAF fed by CO_2 capture and processed via the Fischer-Tropsch method.
Source: Reproduced from Amhamed et al., 2024.[64]

A survey of analyses and reports show a wide range of estimates regarding the 2050 share for Electro-SAFs among SAFs overall, but the average is about 50 percent.[65] A more recent IATA report, however, put the PtL/Electro-SAF percentage at just 14 percent in 2045 and 35 percent in 2050.[66] As we will see below, any estimation of future utilization is highly speculative and almost certainly inadequately mindful of limits to renewable electricity supplies and green hydrogen production capacity (Ch. 14). Though projected to scale up to hundreds-of-billions of litres in just 25 years, Electro-SAF production is rare today, wholly reliant on government subsidies, and projected to remain far more expensive than alternatives.[67]

The case for Electro-SAFs

One could assert that Electro-SAF is SAF done right. The process requires no biological inputs so there are no food-price or land-use impacts. There are no negative effects on soils, sequestration rates, or agricultural GHG emissions. Also, without the need for inputs beyond electricity, water, and air, Electro-SAF is, in theory, not feedstock limited.

Perhaps most important, Electro-SAFs can be truly zero-emission (assuming all processes, fuel transport, etc. are energized by clean, renewable electricity). This is unlike Bio-SAF {seeds}, which will always have large emissions footprints from fertilizer use, etc.

In effect, Electro-SAFs enable jets to be powered by solar panels and windmills, via liquid Electro-SAF energy-carrier intermediaries.

64 Abdulkarem I. Amhamed et al., "Alternative Sustainable Aviation Fuel and Energy (SAFE)- A Review with Selected Simulation Cases of Study," *Energy Reports* 11 (June 1, 2024): fig. 9, https://doi.org/10.1016/j.egyr.2024.03.002.
65 International Air Transport Association et al., "Aviation Net-Zero CO2 Transition Pathways: Comparative Review," tbl. 4.
66 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 2.
67 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 23.

The case <u>against</u> electro-SAFs

> "CO_2 could not be more different than conventional petroleum feedstock; CO_2 has no intrinsic energy content, is nearly 73% oxygen by mass, and is completely devoid of hydrogen. Therefore, whereas petroleum starts from a place of molecules with high molecular weight and high energy that are cracked down to size, CO_2 must be reconstructed molecule by molecule via energy-intensive processes to establish new carbon-carbon and carbon-hydrogen bonds to create fuels and products. While the precise energy demand depends on the conversion process utilized, estimates suggest an energy intensity on the order of 100 kWh required per gallon of CO_2-derived SAF. This implies that [the U.S. 2050 target of] 35 billion gallons of SAF would require 3,500 TWh, *about 85% of the current total U.S. electricity generation* of 4,100 TWh" [italics added].
> —U.S. Department of Energy, National Renewable Energy Lab (NREL), 2024.[68]
>
> "Energy required to produce the 12 Mt of power-to-liquid e-jet fuel required in the UK: 468–660 TWh. 2020 UK electricity generation: 306 TWh."
> —The Royal Society, 2023.[69]
>
> "Lufthansa boss Carsten Spohr has claimed that to power his airline's fleet with e-fuels would use the equivalent of half of Germany's total electricity capacity."
> —Simplifying, 2024.[70]

Not surprising, Electro-SAF is too good to be true. Indeed, as we make hard decisions on the road to a net-zero 2050, our first question must be: is it real? Can it ever be cost-competitive and scale up to provide hundreds-of-billions of litres of fuel per year? Most important, can it do so by 2050, given that it is largely a set of small pilot projects today, with per-litre costs that are a multiple of conventional Jet A and even other SAFs.[71]

There are many reasons to question the feasibility and reality of Electro-SAF; the first is its energy requirement. Another thought experiment: if Electro-SAF provided the entire 2050 supply, how much clean, renewable energy would be needed? Scaling up from the US numbers—100 kWh per US gallon—we can calculate a global 2050 energy requirement of 16.9 trillion kilowatt hours (16.9 petawatt hours) to produce the 169 billion US gallons projected for that year. That number of petawatt hours is equal to just over half the current global electricity production (which is 29 petawatt hours per year). The IATA confirms this calculation, noting that to make even a significant portion of the SAF needed in 2050 could require "roughly the equivalent of half of all electricity produced globally in 2021...."[72]

Electro-SAFs are energy-inefficient in the extreme. This is a result of a core aspect of these fuels: Electro-SAFs seek to run entropy backwards—to unburn hydrocarbons. While combustion turns hydrocarbon fuels such as Jet A into CO_2 and water and in-so-doing releases energy, the processes that create Electro-SAF do the reverse: inject energy into the system to turn CO_2 and water into fuels. Figure 8 shows the simplified chemical reaction for combustion of jet fuel and its reverse: a simplified equation for injecting energy and making new fuels from CO_2 and water. (Note that jet fuel is a mixture of hydrocarbons, primarily 9–16 carbons each, and this equation uses a representative 10-carbon molecule: dodecane.)

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68 Grim et al., "The Challenge Ahead," 4.

69 The Royal Society, "Net Zero Aviation Fuels: Resource Requirements and Environmental Impacts" (London: The Royal Society, February 2023), tbl. 5, https://royalsociety.org/-/media/policy/projects/net-zero-aviation/net-zero-aviation-fuels-policy-briefing.pdf.

70 SimpliFlying and Sustainable Aviation Futures, "Pathways to Sustainable Aviation Fuel: North American Edition," 49.

71 International Civil Aviation Organization, "SAF Rules of Thumb," accessed March 4, 2024, https://www.icao.int/environmental-protection/Pages/SAF_RULESOFTHUMB.aspx.

72 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 2.

Combustion

$$2\,C_{10}H_{22} + 31\,O_2 \rightarrow 20\,CO_2 + 22\,H_20 + \textit{energy out}$$

(2 dodecane + 31 oxygen → 20 carbon dioxide + 22 water + energy out)

Reverse combustion, i.e., creation of Electro-SAFs

$$\textit{Energy in} + 20\,CO_2 + 22\,H_20 \rightarrow 2\,C_{10}H_{22} + 31\,O_2$$

(Energy in + 20 carbon dioxide + 22 water → 2 dodecane + 31 oxygen)

Figure 8. Chemical reactions of combustion and reverse-combustion to produce Electro-SAF.

The energy input in the bottom equation in Figure 8 will have to be very large. Running entropy backwards to produce Electro-SAFs requires an energy input almost three times as large as the fuel's eventual energy output: roughly 100 kWhs per gallon energy input versus 37 kWhs energy output when the fuel is burnt. Producing Electro-SAF squanders nearly two-thirds of the renewable energy input.

Another way of thinking about the energy inefficiency of Electro-SAF is to perceive it as a liquid battery. It is an energy-carrier—packaging renewable electricity into a liquid form compatible with existing jet engines. Just as in a normal battery, electrical energy is added in to change the states of the battery's chemical components. The same is partly true here. But instead of discharging the chemical-energy bonds back to electricity (as could occur in a fuel cell), they are combusted for heat.

The industry notes that "The overall energy efficiency of the e-fuel production process can be as low as 20%, meaning that a large amount of renewable electricity is required to produce a relatively small amount of fuel."[73] This inefficiency is a crucial consideration. Electro-SAF-powered planes would be among the least energy-efficient transportation systems on Earth. In Chapter 20, we compare the efficiency (energy per person-kilometre) of Electro-SAF-powered planes to renewable-electricity-powered trains and ask: In a climate emergency; as we struggle to electrify vehicles, industry, home heating, etc.; as we face inadequate supplies of clean, renewable energy for decades to come; is it responsible public (or private) policy to spend trillions to create one of the least-energy-efficient transportation systems possible? Is it prudent to build out an Electro-SAF aviation system that uses more than three times[74] as much scarce clean energy per passenger kilometre as alternatives such as high-speed trains?

Finally, the efficiency and cost situation may be even worse than outlined above. Plucking carbon directly from the air (direct air capture, DAC) remains highly uncertain, as do energy requirements and costs. And there is the scale-up problem. This assessment from airline industry group IATA:

> "The largest carbon capture plant in the world in 2023 had a 4,000 tonne per year (t/y) nominal capacity but Climeworks, the company behind the project, has plans for a plant ten times that size to start operating in 2025. Carbon Engineering ... has future projects with a planned capacity of 1 million t/y by 2026. The PtL route alone will need more than 500 million t/y in terms of captured carbon inputs by 2050, showing the size of the scale-up required."[75]

To summarize: though no large DAC plants now exist, IATA projects that the fuel industry will need to complete 500 by 2050—completing one every three weeks. Relevant to this scale-up challenge: one of the largest DAC projects announced so far—the Bison Project in Wyoming—was put on hold as a result of insufficient clean energy supplies because of competition from data centres and artificial intelligence (AI).[76]

73 SimpliFlying and Sustainable Aviation Futures, "Pathways to Sustainable Aviation Fuel: North American Edition," 49.

74 More likely, trains are six times as energy efficient (rather than three times), but, below, we credit SAF-powered aviation with a speculative/hypothetical 2x efficiency gain in order to satisfy those who would have us believe that innovation will significantly boost efficiency. See Ch. 20.

75 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 5.

76 Vasil Velev, "CarbonCapture Inc. Pauses Development Of Project Bison In Wyoming," *Carbon Herald* (blog), September 1, 2024, https://carbonherald.com/carboncapture-inc-pauses-development-of-project-bison-in-wyoming/.

7. Land Use Change and Emissions from SAFs

Burning conventional jet fuel (Jet A) releases carbon dioxide (CO_2) and other GHGs totalling 89 grams of carbon dioxide equivalent (CO_2e) per megajoule of energy.[77] 89 grams CO_2e/MJ is Jet A's emissions intensity. Each SAF produced from the various feedstock/production-process combinations has its own emissions intensity and that intensity will differ for fuels produced from feedstocks from different regions.

Most simply, the emissions intensity of a SAF is made up of two main components:

1. **Core life-cycle** emissions—the GHGs released from producing, collecting, and processing the feedstock into the SAF and transporting the SAF; and

2. **Induced land use change** (ILUC) emissions—often soil carbon released when production of a feedstock is modelled as causing a shift in production/demand to another place and, as a result, the creation of new farmland from forests or grasslands.

Examples of #1, core life-cycle emissions, could include those from fertilizer use or tractor fuel if the feedstock is canola or corn or a purpose-grown energy crop.

This report is agnostic regarding whether the emissions calculated by ICAO/CORSIA for each SAF feedstock/production-process pairing are correct. Those wanting to delve deeper into such questions are directed toward two reports: *CORSIA Methodology for Calculating Actual Life Cycle Emissions Values* (40 pages)[78] and *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels* (7 pages).[79] For a deeper dive, consider the 203-page *CORSIA Eligible Fuels – Life Cycle Assessment Methodology*.[80]

To begin to better understand how ICAO models its emissions values, it is important to know:

A. It is assumed that there are no *combustion* emissions, as the CO_2 coming out of the jet engine is equal to CO_2 that was photosynthesized into the biomass feedstock (or was captured from the air in Electro-SAF).

B. Emissions values may be lower than many expect, because a portion of emissions (from on-farm diesel fuel or fertilizer use, for instance) are assigned to co-products. E.g., when SAF is made from soybeans, a portion of the emissions from on-farm production is assigned to the soybean oil that goes into making SAF, but another portion of the emissions is assigned to the meal destined for cattle feeding. Emissions can be split between SAFs and co-products in various ways: by the dollar value of each, by mass, or by energy content. ICAO/CORSIA uses the latter.[81]

C. Wastes and residues, such as grain straw or corn stover or forest trimmings, are assumed by ICAO/CORSIA to have zero emissions from Induced Land Use Change (ILUC).[82]

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77 Air Transport Action Group, "Beginner's Guide to Sustainable Aviation Fuel," 2.

78 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values" (CORSIA and ICAO, June 2022), https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

79 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels" (CORSIA and ICAO, June 2022), https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

80 ICAO, "CORSIA Eligible Fuels – Life Cycle Assessment Methodology" (ICAO, June 2022), https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf.

81 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values," 5, point 6.

82 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values," Page 5, point 7.

D. Wastes and residues, such as grain straw or corn stover or forest trimmings, are assumed to have zero emissions from production, though emissions from collection and processing are counted.[83]

E. ICAO/CORSIA offers options to reduce ILUC including the "yield increase approach" and the "unused land approach."[84] The former invites SAF makers to show that the feedstock is created as a result of somehow increasing output and the latter invites them to show that the feedstock comes from land that has not recently (i.e., the past five years) been in agricultural production.

F. For some energy crops, the ILUC value is *negative*—based on the notion that although there are land use changes (i.e., growing energy crops in some places may cause forest or grassland to be converted to farmland in other places) the soil carbon sequestration effects of growing these woody and grassy energy crops are so large as to wholly offset and reverse those LUC effects. Much more assessment is needed of this questionable assumption. For example, soils eventually "fill up" with carbon—they reach maximal "saturation" levels and cease sequestering new carbon. It is not clear how ICAO/CORSIA values incorporate this reality.

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Global	Agricultural residues	Residue removal does not necessitate additional nutrient replacement on the primary crop	7.7		7.7
Global	Forestry residues		8.3		8.3
Global	Municipal solid waste (MSW), 0% non-biogenic carbon (NBC)		5.2	0.0	5.2
Global	Municipal solid waste (MSW) (NBC given as a percentage of the non-biogenic carbon content)		NBC*170.5 + 5.2		NBC*170.5 + 5.2
USA	Poplar (short-rotation woody crops)		12.2	-5.2	7.0
Global	Poplar (short-rotation woody crops)		12.2	8.6	20.8
USA	Miscanthus (herbaceous energy crops)		10.4	-32.9	-22.5
EU	Miscanthus (herbaceous energy crops)		10.4	-22.0	-11.6
Global	Miscanthus (herbaceous energy crops)		10.4	-12.6	-2.2

Figure 9. Selected examples of CORSIA life cycle emissions values for SAFs produced via Fischer-Tropsch.
Source: Reproduced from ICAO, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels."[85]

Note in Figure 9 that ICAO/CORSIA assigns to agricultural residues a core LCA of 7.7 grams CO_2e emissions per MJ of energy and assigns zero for land-use change, for a total of 7.7 grams CO_2e per MJ. This is well below the 89 grams CO_2e per MJ produced when conventional, fossil-fuel Jet A is combusted. Note also the proviso: "residue removal does not necessitate additional nutrient replacement on the primary crop." This raises questions, as every tonne of residue removed takes with it a quantity of nitrogen, phosphorus, potassium, and micro-nutrients.[86]

83 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values," Page 5, point 8.

84 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values," 12.

85 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels," tbl. 1.

86 Gould, "Corn Stover Harvesting."

Note also in Figure 9 that the energy crop miscanthus is assigned a negative value for land-use change (because of assumed high rates of sequestration) and a negative value overall. The contention is that burning SAF made from miscanthus feedstock would be net-negative—that it would sequester more soil carbon from the atmosphere than its production and processing would emit.

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Global	Tallow		22.5	0.0	22.5
Global	Used cooking oil		13.9		13.9
Global	Palm fatty acid distillate		20.7		20.7
Global	Corn oil	Oil from dry mill ethanol plant	17.2		17.2
USA	Soybean oil		40.4	24.5	64.9
Brazil	Soybean oil		40.4	27.0	67.4
Global	Soybean oil		40.4	25.8	66.2
EU	Rapeseed oil		47.4	24.1	71.5
Global	Rapeseed oil		47.4	26.0	73.4

Figure 10. Selected examples of CORSIA life cycle emissions values for SAFs produced via HEFA.
Source: Reproduced from ICAO, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels."[87]

Notice in Figure 10 that emissions from both soybean and canola ("rapeseed") feedstocks are in the mid-60s and mid-70s, far above the 44.5 grams CO_2e per MJ (half of the 89 grams from Jet A) needed to qualify for subsidies under US *Inflation Reduction Act* rules. This is why US farmers and governments are pushing for a recalculation using the made-in-the-USA GREET modelling system.[88] Below, in Figure 11, the same problem is visible for corn-based SAF. And, again, the solution is to recalculate using GREET.

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Global	Agricultural residues	Residue removal does not necessitate additional nutrient replacement on the primary crop.	29.3	0.0	29.3
Global	Forestry residues		23.8		23.8
Brazil	Sugarcane	Standalone or integrated conversion design	24.0	7.3	31.3
Global	Sugarcane	Standalone or integrated conversion design	24.0	9.1	33.1
USA	Corn grain	Standalone or integrated conversion design	55.8	22.1	77.9
Global	Corn grain	Standalone or integrated conversion design	55.8	29.7	85.5
USA	Miscanthus (herbaceous energy crops)		43.4	-54.1	-10.7
EU	Miscanthus (herbaceous energy crops)		43.4	-31.0	12.4
Global	Miscanthus (herbaceous energy crops)		43.4	-23.6	19.8
USA	Switchgrass (herbaceous energy crops)		43.4	-14.5	28.9

Figure 11. Selected examples of CORSIA life cycle emissions for SAFs produced via alcohol to jet (AtJ).
Sources: Reproduced from ICAO, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels."[89]

87 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels," tbl. 2.
88 Kentucky Corn Growers Assoc., "A Farmers Guide to the GREET Model."
89 Carbon Offsetting and Reduction Scheme for International Aviation and International Civil Aviation Organization, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels," tbl. 3.

"Marginal land"

Above, this report quoted the US government as stating that it is not realistic to expect that purpose-grown energy crops will be constrained to marginal or currently unused land. Nonetheless, some SAF proponents including ICAO/CORSIA wish to minimize land-use change emissions from purpose-grown energy crops by asserting that such crops will be largely planted and harvested on marginal, degraded, abandoned, or unused land.[90] This raises many questions. Where in the world are farmers choosing not to utilize viable land? Alternatively, if land appears "unused," might it be providing ecosystem benefits and habitat? How does the community adjacent to that unused or abandoned land understand its value and function? Is it used by anyone or for any purpose? Is it used by grazers or gleaners or hunters or gatherers? Is it a commons, perhaps held temporarily out of production to mitigate risks of droughts or food shortfalls? Are these marginal or unused acres currently delivering ecosystem services—as watersheds, carbon sinks, biodiversity reserves, or refugia for birds and other animals?

Thus, we have two issues related to land-use change: 1. Purpose-grown energy crops will take prime farmland and will not be confined solely to surplus acres: unused, abandoned, degraded, or marginal areas; and 2. Even where energy crops are confined to such areas, they may displace other traditional land uses (grazing, commoning, gleaning, hunting, shifting cultivation, etc.) and ecosystem services (wildlife habitat, water purification, pollinator habitat, etc.).

[90] International Air Transport Association, "SAF Handbook," 15.

8. Land Use Change and Demands Upon Our Earth, *The Big Picture*

> "The demand for harvestable biomass (food, fuel, and fibre) by a growing, wealthier, and increasingly urbanized global human population is placing relentless pressure on the Earth's ecosystems. To a large extent, this demand has been met by converting [natural] ecosystems into production ecosystems—ecosystems modified for the production of one or a few harvestable species.... Although these alterations occur at local scales, their cumulative effect is causing global transformation of the Earth's biosphere.... Humans have already altered more than 75% of the world's terrestrial habitats—nearly 40% of all productive land has been converted into agricultural areas and two thirds of all boreal forests are under some form of management, mainly for wood production...."
> —Nyström et al., *Nature*, 2019.[91]

The preceding chapter looks narrowly and technically at land-use change, but a big-picture, long-term view is even more revealing.

Take 1

Consider SAFs within the larger context of what humans are going to attempt this century:

- Feed two billion more people as our population rises past 10 billion and
- Feed those hundreds-of-millions who do not today have enough to eat and
- Expand a high-land-requirement meat- and dairy-heavy diet to billions more people as populations grow and purchasing power increases (many analysts estimate that global grain production must rise by roughly 50 percent by mid-century, as a result of rising populations, incomes, and meat consumption[92]) and
- Produce biomaterials to replace petroleum plastics and
- Produce more land-sourced biofibres (cotton, hemp, linen, wool) to replace petro-fibres and to clothe a larger population with enlarged purchasing capacities and
- Produce and remove from the land billions of tonnes of energy-system biomass annually for BECCS and
- Produce and remove billions of tonnes of energy-system biomass annually for SAFs and
- Produce the preceding billions of tonnes of food, fibre, and feedstocks even as the global climate deteriorates and impacts on farmers intensify and
- Maximize soil health, soil building, and soil carbon sequestration and
- Find land areas to plant trees in order to draw down CO_2—two billion trees in Canada and perhaps a trillion globally[93]—and
- Do the preceding while simultaneously working to reduce nitrogen fertilizer use—global use of which has now far exceeded planetary boundaries and
- Do all the preceding while trying to use less farmland, in an effort to reverse habitat destruction which is now driving the fastest extinction event in 65 million years.

Placing SAFs in the context of these many proposed 21st century megaprojects leads us to ask: Is there enough land?

91 Magnus Nyström et al., "Anatomy and Resilience of the Global Production Ecosystem," *Nature* 575, no. 7781 (November 7, 2019): 98.
92 "World must sustainably produce 70 per cent more food by mid-century – UN report," United Nations, UN News, Dec. 3, 2013, https://news.un.org/en/story/2013/12/456912
93 Maxine Joselow, "Republicans Want to Plant a Trillion Trees. Scientists Are Skeptical.," *Washington Post*, August 2, 2023, https://www.washingtonpost.com/climate-environment/2023/08/02/trillion-trees-republicans-climate/ .

Take 2

Let's push SAF out of the centre of our attention and start with a clean sheet of paper. Let's ask: if we really have hundreds-of-millions of acres of farmland not needed for the project of feeding people, what is the best use of that land? Perhaps it would be best to give it back to nature—to slow extinction, create refuges for fast-disappearing birds and other wild animals, protect watersheds and aquifers, maximize soil health and sequestration, and serve as a strategic reserve of potential foodland acres should it turn out that feeding the ten billion amid a deranged climate is harder than we imagine. Alternatively, perhaps it would be best to use that land to plant trees—biological, zero-energy-demand carbon-removal devices that simultaneously provide habitat, beauty, recreation, and spiritual renewal. Using land for tree-planting is negative-emission, whereas using that land for SAF feedstocks produces emissions. As we slide into the jaws of an intensifying polycrisis, we should ask: What is humanity's best use of these hundreds-of-millions of acres? It is unlikely that the answer is: to fuel vacation jets.

Take 3

Those who promote land-based energy systems—SAFs, automobile biofuels, BECCS, etc.—suffer from historical amnesia: they forget the step-by-step process over the past several centuries that led us to this point. Here is a quick reminder of our history and our path to the present.

For many thousands of years, until about three centuries ago, virtually all energies for human systems were sourced from the land. Food energy was land-sourced, of course. But so, too, was heating energy—taken mostly from forest land as firewood, with small additions from dung, straw, peat, etc. Traction and transport energy, too—the energy for horses, oxen, and draft animals—was similarly sourced from the land, as grass, grain, and fodder. The land provided all energies: for heat, food, and movement.[94]

This universal dependence on land-sourced energies imposed limits on human societies and economies. Everything was a trade-off. Cut down forests to create more land to produce food energy and you have less heating energy. Use your farmland acres to grow more fodder and create more pasture for transport and traction energy (horses and oxen) and you have less food energy. For thousands of years, these limits and trade-offs throttled back the growth of human economies and populations, with famine and die-off often being the result of hitting these limits.

Moving forward from that period centuries ago, we see that, one after another, energy demands were *removed* from the land. The first energy demand removed from the land was heating—we began to get more of our heat from coal and less from wood. Next, we began to remove from the land the requirement to provide energy for transport. Trains energized by coal replaced horses and carriages energized by land-sourced grasses, grains, and fodders. Somewhat later, with the proliferation of oil and the creation of the internal combustion engine, we fully removed from the land, in many places, the requirement to provide energy for transport and traction. In places such as North America and Europe, the land was relieved of all demands save for the provision of food energy for people.

But now, seemingly forgetting the steps that led us to our soon-to-be-ten-billion-person mega-civilization, we are about to embark on multiple projects that reimpose onto our landbase requirements to provide heat energy (BECCS electricity to heat homes, etc.) and transport energy (SAFs). That *may* be possible, but a default assumption should probably be that it is not. Moreover, resuming reliance on land-sourced heating and transport fuels should not be seen as some dazzling new high-tech move into the future, but rather a move backward into our past. With SAFs from willow and poplar, we are literally

94 A couple minor exceptions exist: wind-powered sailing ships and water- and wind-powered mills.

considering wood-fired passenger jets (though, admittedly, with exotic-chemistry intermediaries to transmogrify that firewood into kerosene-like liquid fuels).

Figure 12 shows how, over the course of building our mega-civilization, biomass was supplanted by fossil fuels. SAF proponents would have us believe we can now reverse this process: replacing fossil fuels with biomass.

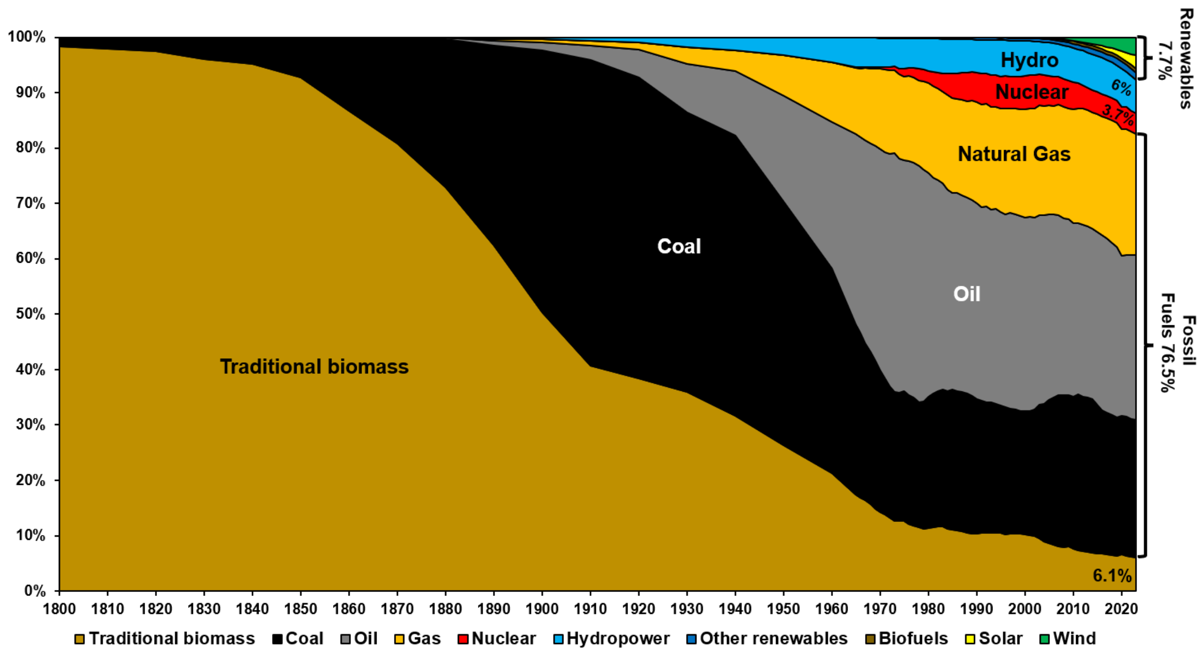

Figure 12. World Primary Energy Consumption, 1800–2023.
Sources: David Hughes, Global Sustainability Research Inc., with data from Energy Institute and Vaclav Smil.[95]

Take 4

Staying with the big picture, as we contemplate removing billions of tonnes of biomass annually, we can acquaint ourselves with the concept of HANPP: Human Appropriation of Net Primary Productivity.

Green plants and other photosynthesizing organisms (incl. algae and bacteria) create solar-energized carbon-rich biomass, the food-energy basis of virtually all life on Earth. "Net primary productivity" (NPP) is the term scientists use when quantifying the tonnage of carbon photosynthesized into organic matter. When plants turn sunlight, water, CO_2, and nutrients into new biomass—roots, stems, trunks, branches, leaves, flowers, fruits, and seeds/grains—those plants create NPP.

"Human appropriation of net primary productivity" (HANPP) is the term scientists use to quantify the portion of annual plant biomass production taken and used by humans: for food, fibre, livestock feed, building materials, paper products, heating fuels, etc. HANPP is a measure of humanity's draw upon the biosphere, and that measure is high: Humans are appropriating nearly 30 percent of terrestrial aboveground NPP—nearly 30 percent of the plant biomass tonnage that grows on land worldwide.[96] This is a remarkable draw for just one species. Until recent centuries, no single species appropriated more than 1 or 2 percent of NPP.

95 Energy Institute, "Statistical Review of World Energy," 73rd ed. (London: EI, 2024); Vaclav Smil, *Energy Transitions: Global and National Perspectives*, 2nd ed. (Santa Barbara, California: Praeger, 2016).

96 Helmut Haberl et al., "Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems," *Proceedings of the National Academy of Sciences* 104, no. 31 (July 31, 2007): 12943. See also Peter Vitousek et al., "Human Appropriations of the Products of Photosynthesis," *Bioscience* 36, no. 6 (June 1986): 368 & 372. Vitousek estimates HANPP at nearly 40 percent.

Our high rate of HANPP matters for at least two reasons: First, all animals feed on NPP (either directly by eating plants or indirectly by eating animals that eat plants) so, when humans take more we leave other species less. Second, HANPP is a proxy for how much productive land area we have taken for our own—how much physical and biological space we are occupying on the planet.

And though this overall HANPP percentage is high, regional figures in much of Europe and Asia are even higher: above 70 percent.[97] Scientists such as Katherine Richardson, Will Steffen, and Johan Rockström, looking at safe operating limits for planet Earth, conclude that "HANPP is well beyond a precautionary planetary boundary aiming to safeguard the functional integrity of the biosphere and likely already into the high-risk zone."[98]

Take 5

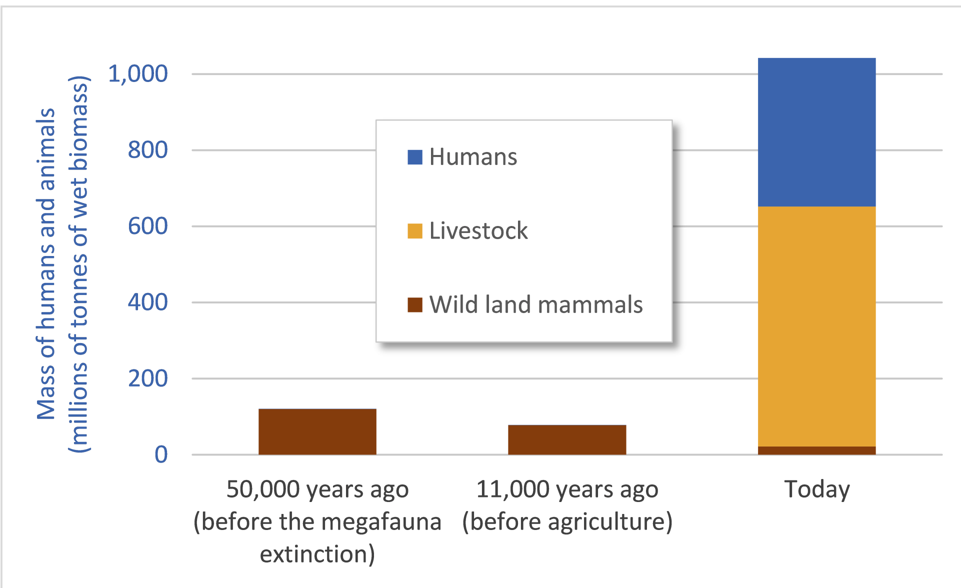

Figure 13. Mass of humans, livestock, and terrestrial wild animals, selected periods.
Sources: Bar-On, Phillips, and Milo; Barnosky; and Smil.[99]

Figure 13 provides another view of humanity's annexation of Earth's NPP and land area. It shows the mass of humans (blue), our livestock (tan), and terrestrial wild mammals (brown). Three periods are shown. On the left is the period 50,000 years ago: before humans were significant factors in most of Earth's ecosystems. In the middle is the period around 11,000 years ago: after humans had spread over most of the Earth but before we began practicing agriculture. (On both the left and in the centre, the mass of humans is very small and not visible on the graph.) On the right is the situation today: We and our livestock dominate the Earth.

97 Helmut Haberl et al., "Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems," *Proceedings of the National Academy of Sciences* 104, no. 31 (July 31, 2007): 12943. See also Peter Vitousek et al., "Human Appropriations of the Products of Photosynthesis," *Bioscience* 36, no. 6 (June 1986): 368 & 372. Haberl, Table 3, lists rates of NPP appropriation for Europe and Asia as 35 percent to 63 percent (excl. Central Asia and Russian Federation). These NPP percentages include above- and below-ground biomass. Thus, above-ground-only values would be about 15 percent higher than figures in Table 3. Also, see Marc Imhoff et al., "Global Patterns in Human Consumption of Net Primary Production," *Nature* 429 (June 24, 2004): 872. Imhoff et al. list human appropriations of NPP in Western Europe as 72.22 percent and in south-central Asia as 80.39 percent.

98 Katherine Richardson et al., "Earth beyond Six of Nine Planetary Boundaries," *Science Advances* 9, no. 37 (2023).

99 Yinon Bar-On, Rob Phillips, and Ron Milo, "The Biomass Distribution on Earth," *Proceedings of the National Academy of Sciences* 115 (2018); Anthony Barnosky, "Megafauna Biomass Tradeoff as a Driver of Quaternary and Future Extinctions," *Proceedings of the National Academy of Sciences* 105 (2008); Vaclav Smil, *Harvesting the Biosphere* (Cambridge, MA: MIT Press, 2013).

The biomass of humans and our livestock outweigh remaining wild animals 32-to-1, with wild species making up *just 3 percent of terrestrial animal biomass*. This unprecedented mass of humans and livestock upon the Earth has been enabled by humanity's seizure of land for grazing, feedgrain production, and food-crop production—our multiplication of HANPP. And this massive human land-taking is the main reason why the Earth is now undergoing the most rapid extinction event in 65 million years.[100]

The most comprehensive study of life on Earth ever undertaken, the 1,100-page *Global Assessment Report on Biodiversity and Ecosystem Services*, compiled by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), tells us that:

> "The global rate of species extinction is already at least tens to hundreds of times higher than the average rate over the past 10 million years and is accelerating.... Habitat loss and deterioration, largely caused by human actions, have reduced global terrestrial habitat integrity.... Around 9 per cent of the world's estimated 5.9 million terrestrial species—*more than 500,000 species—have insufficient habitat for long-term survival, and are committed to extinction, many within decades, unless their habitats are restored...*" [italics added].[101]

Another study found that "Most of the 177 mammal species we sampled have lost more than 40% of their geographic ranges in historic times, and *almost half have lost more than 80% of their ranges in the period* ~1900–2015" and that "as much as 50% of the number of animal individuals that once shared Earth with us are already gone, as are billions of populations."[102]

In light of the preceding, any planetary megaproject to utilize hundreds of millions of acres of land and extract billions of tonnes of biomass to produce energy, biomaterials, etc. should be looked at with *extreme* thoroughness, caution, and *scepticism*. Scientists estimate that we are already exceeding, by 60 percent, sustainable levels of human appropriation of net primary productivity (HANPP).[103] Yet SAFs are a massive planetary appropriation of yet more NPP. Research by Milo, Bar-On, and others (see Figure 13, above) shows that we have slashed the mass of wild animals, largely as a result of our extraction of biomass, annexation of land, destruction and fragmentation of habitat, and destruction and degradation of remote and wild places. It is in this context that we now contemplate extracting billions of tonnes more biomass to fuel vacation jets. If there is land that is not needed to feed hungry people, and if we have already exceeded the sustainable removal of biomass by perhaps 60 percent, then the wisest move would be to reduce our farmland area and reduce our draws upon the biosphere's plant mass so as to leave space for other species and return HANPP back to within planetary boundaries. And if this reduced farmland area can host grass and trees and thereby draw down carbon/CO_2 and slow warming, we gain yet another benefit.

100 Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis, 2005, (Island Press, Washington), 5, 36, & 38.
101 IBPES et al., "The Global Assessment Report on Biodiversity and Ecosystem Services" (Bonn: IBPES, 2019), XXVII.
102 Gerardo Ceballos, *The Annihilation of Nature: Human Extinction of Birds and Mammals* (Baltimore: Johns Hopkins University, 2015).
103 Justin D. K. Bishop, Gehan A. J. Amaratunga, and Cuauhtemoc Rodriguez, "Quantifying the Limits of HANPP and Carbon Emissions Which Prolong Total Species Well-Being," *Environment, Development and Sustainability* 12, no. 2 (April 1, 2010): 213, https://doi.org/10.1007/s10668-009-9190-7.

9. SAFs and Water

> "The world is facing an imminent water crisis, with demand expected to outstrip the supply of fresh water by 40% by the end of this decade.... Governments must urgently stop subsidising the extraction and overuse of water through misdirected agricultural subsidies, and industries from mining to manufacturing must be made to overhaul their wasteful practices, according to a landmark report on the economics of water."
> —*The Guardian*, 2023.[104]
>
> "With more than 733 million people currently living in areas of high or critical water stress ... and a projected 30% increase in global water demand by 2050 compared to 2010 ..., the role of water access, allocation, and management is key for sustainable economic development. To feed a projected global population of 10 billion in 2050, agricultural production will need to increase by almost 50% compared to 2012 ..., with much of this growth expected to be achieved through irrigation and water capture and storage...."
> —United Nations, *World Water Development Report*, 2024.[105]
>
> "Without irrigation you just wouldn't have corn on this farm," said [Minnesota farmer Jake] Wildman, who is president of the state's irrigators association. "And the market tells us to raise corn. So you could say that the market is also telling us to irrigate." ... In western Minnesota, applications for new irrigation wells spiked amid the first ethanol boom.
> —*New York Times*, 2023.[106]
>
> "The water footprint of drop-in fuels produced via HEFA from soybean oil has been estimated at between 2 and 309 gallons of water per gallon of fuel, depending on the irrigation method used and location."
> —U.S. Department of Energy, National Renewable Energy Laboratory (NREL), 2024.[107]

This chapter is a one-page stub: a short mention to highlight the importance of the water issue and to ensure that it is considered in future analyses.

Significant portions of both energy production *and* food production are water intensive. Thus, it is wholly foreseeable that the production and processing of SAFs and their feedstocks will be water intensive. Irrigation, likely for many feedstock acres, will multiply that water intensity. It is beyond the scope of this report to detail water use and limitations for SAFs as we move into a world of 10+ billion people. Nonetheless, *existing* water constraints and shortages and projected future increases in water demand all indicate that extreme caution is warranted before investing trillions of dollars in SAF production systems that will consume many trillions of litres of water annually.

Finally, it is important to look beyond *direct* irrigation-water requirements for SAF feedstock acres to the expanding irrigation demands for agriculture overall. The diversion of farmland to SAF production (tens of millions of acres in the US alone) will require intensified food production elsewhere, *indirectly* driving up irrigation and water demands on farmland overall. Even if 100 percent of SAF feedstocks were unirrigated, the land requirements for those feedstocks will trigger intensified food production on farmland elsewhere, and, hence, irrigation. So, just as there is "induced land use change" (ILUC), there is "induced water use change" (IWUC). The latter is almost universally ignored by SAF analysts.

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104 Fiona Harvey, "Global Fresh Water Demand Will Outstrip Supply by 40% by 2030, Say Experts," *The Guardian*, March 17, 2023, sec. Environment, https://www.theguardian.com/environment/2023/mar/17/global-fresh-water-demand-outstrip-supply-by-2030.

105 UN Water and UNESCO, "The United Nations World Water Development Report 2024: Water for Prosperity and Peace" (Paris: UNESCO, 2024), 34.

106 Bearak, Searcey, and Rojanasakul, "Airlines Race Toward a Future of Powering Their Jets with Corn."

107 Oscar Rosales Calderon et al., "Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway" (NREL, July 30, 2024), 28, https://doi.org/10.2172/2426563.

10. SAFs and Planetary Boundaries

> "Earth is now well outside of the safe operating space for humanity. ... As primary production [of biomass] drives Earth system biosphere functions, human appropriation of net primary production [HANPP] is proposed as a control variable for functional biosphere integrity. This boundary is also transgressed."
> —Richardson, Steffen, Rockström, et al., "Earth Beyond Six of Nine Planetary Boundaries," 2023.[108]

In Canada, over the past 31 years, agricultural diesel fuel use has doubled;[109] over the past 18 years, nitrogen fertilizer use has doubled;[110] and over the past 14 years, pesticide use has doubled.[111] Farmers doubled the use of these inputs and others in order to increase output—to add millions of tonnes to the annual amounts of grains, oilseeds, legumes, forage and livestock feed, and other biomass we take from our farm fields. Farmers did so partly because agribusiness corporations have farmers on a treadmill where they are relentlessly spurred to produce more and more. More output requires more inputs, as evidenced by the doubling of fuel, fertilizer, and pesticide use.

Like all human systems—like transport, manufacturing, housing, mining, forestry, fisheries, etc.—agricultural production is creating environmental problems. For agriculture, these problems include GHG emissions, ocean dead zones created by fertilizer run-off, pesticide-induced reductions of insects and birds, tree removal and deforestation, destruction of wetlands, etc.

Again, like all human systems, agriculture is crashing past planetary boundaries. Virtually all human systems are now unsustainable. Agriculture is not an exception—not uniquely sustainable or benign. Nothing in this report is an indictment of agriculture, farmers, or farming, but rather a clear-eyed assessment that in a global petro-industrial system that has moved far outside the safe operating limits of planet Earth, agriculture has done so, too. It is within this context—human systems far outside of sustainable limits and moving farther outside—that we should evaluate SAF proposals.

Over the past decade-and-a-half, scientists Will Steffen, Johan Rockström, Katherine Richardson, and dozens of others have developed and refined the concepts of "planetary boundaries" and "the safe operating space for humanity."[112] Their peer-reviewed academic articles have been published in top journals such as *Nature* and *Science*. In these reports, the authors detail several domains in which humans have pushed farthest past Earth's safe operating limits, including:

1. biodiversity loss (humans are driving the fastest extinction rates in millions of years);
2. nitrogen and phosphorus fertilizer tonnage; and
3. Land-use change (see Figure 14).

108 Katherine Richardson, Will Steffen, Johan Rockström, et al., "Earth beyond Six of Nine Planetary Boundaries," *Science Advances* 9, no. 37 (September 15, 2023).

109 Data provided by Environment and Climate Change Canada (ECCC) upon request; see also National Inventory Report (NIR).

110 Statistics Canada Tables 32-10-0274-01 and 2-10-0039-01.

111 Health Canada, Pest Management Regulatory Agency (PMRA), "Pest Control Products Sales Report," various years (Ottawa: PMRA); United Nations Food and Agriculture Organization (UN FAO), FAOStat: Pesticides Use, https://www.fao.org/faostat/en/#data/RP

112 Johan Rockström et al., "Planetary Boundaries: Exploring the Safe Operating Space for Humanity," *Ecology and Society* 14, no. 2 (2009); Johan Rockström et al., "A Safe Operating Space for Humanity," *Nature* 461, no. 7263 (2009); Wim de Vries et al., "Assessing Planetary and Regional Nitrogen Boundaries Related to Food Security and Adverse Environmental Impacts," *Current Opinion in Environmental Sustainability* 5, no. 3 (2013); Will Steffen et al., "Planetary Boundaries: Guiding Human Development on a Changing Planet," *Science* 347, no. 6223 (2015); Katherine Richardson et al., "Earth beyond Six of Nine Planetary Boundaries," *Science Advances* 9, no. 37 (September 15, 2023).

All these boundary breaches will be exacerbated by the SAF project to produce, remove, process, and combust billions of tonnes of grains, oilseeds, agricultural residues, and energy crops—trees and grasses.

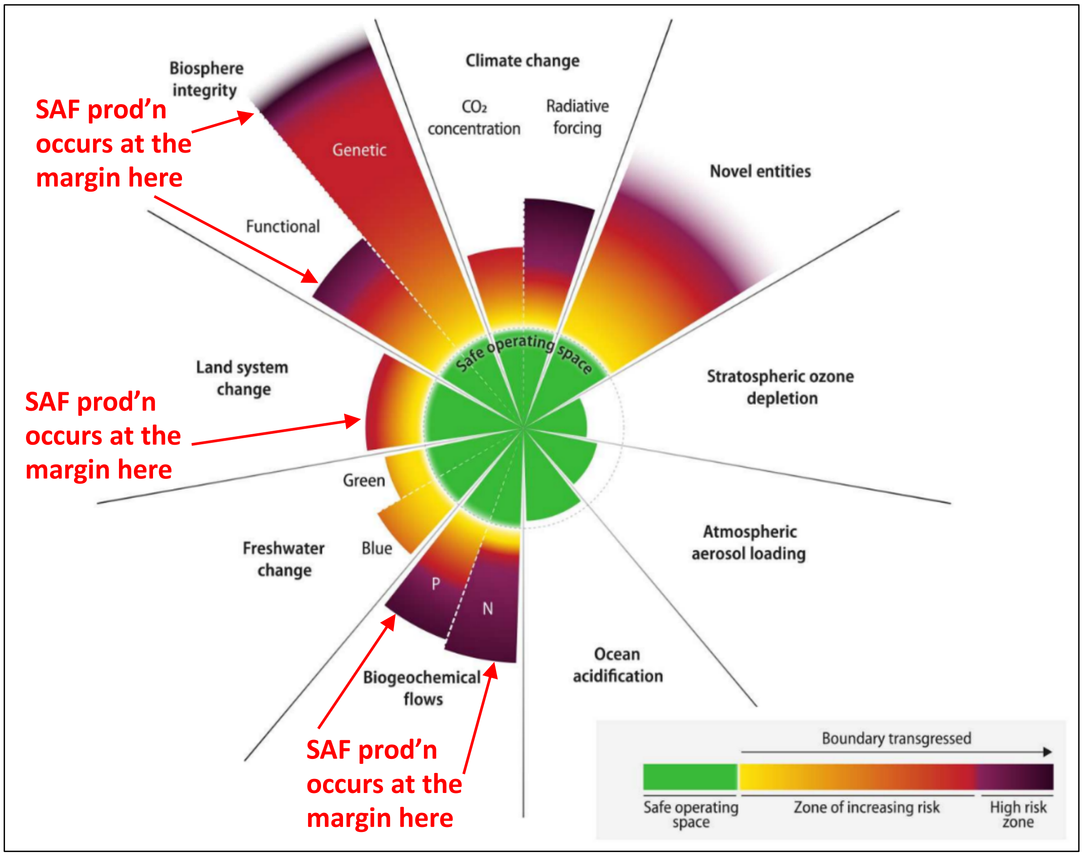

Figure 14. A diagram of human transgressions of planetary boundaries.
Source: Richardson, Steffen, Rockström, et al., "Earth beyond Six of Nine Planetary Boundaries," 2023.[113]
Notes: In the above diagram, under "Biogeochemical flows," N and P are short for nitrogen and phosphorus, i.e., mainly fertilizer use. And "Biosphere integrity" and "Functional" can be thought of as correlating to habitat and species losses.

Crucial to understand is this: even if SAF production is wholly neutral in its impacts on the environment—with no new or additional adverse effects—even if, by some unexpected miracle, it in no way makes things worse, it will still be unsustainable, because most metrics are already well into unsustainability territory. SAF production will take place at the margins—on the outer edge of those red/purple wedges above—far outside the sustainability space. If nitrogen flows are already unsustainable (see N wedge at bottom), flowing in more nitrogen to produce SAF feedstocks cannot be sustainable. Similarly, if biomass removal (HANPP) is already unsustainable, the additional biomass required by SAFs cannot be produced sustainably. If land system change is already unsustainable, allocating millions of acres to fuel production cannot be sustainable. *Sustainable* Aviation Fuel is a misnomer.[114]

113 Katherine Richardson, Will Steffen, Johan Rockström, et al., "Earth beyond Six of Nine Planetary Boundaries," *Science Advances* 9, no. 37 (September 15, 2023): Fig. 1.

114 One of the expert reviewers who read a draft of this report pointed out that the UN agency International Civil Aviation Organization (ICAO)—the agency that oversees CORSIA—has engaged with civil society and non-governmental organizations (NGO) regarding sustainability, biodiversity, food security, etc. This NFU report has not accessed information on that process but will endeavour to do so and to understand ICAO's consultation process and how that may have shaped the global SAF initiative.

11. SAFs and Food Prices

> "Following an intense lobbying campaign by the [U.S.] ethanol industry, the Treasury's recent guidance allows for the use of an alternative model, a version of GREET [Greenhouse gases, Regulated Emissions, and Energy use in Transportation], which opens the door for corn ethanol and other crop-based biofuels to qualify for the credit. Major U.S. airlines supported the ethanol industry's push despite previously agreeing that SAF production should not compete with food production."
> —World Resources Institute, 2024.[115]
>
> "I do worry over the longer term, though, on sustainable aviation fuels … what's that going to do to food prices going forward? ... I think we're going to reach a point in the next 10 or 20 years where there will be challenges posed not just for the airline industry, but for industry in general, around sustainable aviation fuels where it may have an upward impact on food prices."
> — Michael O'Leary, CEO of Ryanair, 2021.[116]
>
> "The Renewable Fuel Standard (RFS) specifies the use of biofuels in the United States and thereby guides nearly half of all global biofuel production.... We find that the RFS increased corn prices by 30% and the prices of other crops by 20%...."
> —Lark et al., "Environmental Outcomes of the US Renewable Fuel Standard," 2022.[117]
>
> "As a response to higher crop prices encouraged by biofuel production, households and firms will *reduce their crop consumption* or increase the consumption of their substitute" [italics added].
> —Zhou et al., "Estimated Induced Land Use Change Emissions....," 2021.[118]

SAF may come to stand for "Sacrificing Affordable Food." It is likely that entire reports will be needed on this important topic. Here, we simply raise the issue and begin to sketch the magnitude of the problem.

Perhaps anecdotally, Global olive oil prices have doubled over the past three years (though, admittedly, climate-related production problems have played a role).[119] In Canada, margarine, made from canola oil, is up 40 percent since 2022.[120] But perhaps this is not anecdotal: analysts are now talking about the coming "big oil deficit" driven by biofuel/vegetable-oil demand set to "explode."[121]

It is hard to predict the magnitude of food-price impacts because there are many unknowns:

- How sincere and committed are airlines and fuel providers to actually undertaking the herculean scale-up needed to reach future SAF supply targets?
- How much SAF feedstock will come from conventional crops such as corn, soy, and canola?
- To what extent will any expansion of those crops displace other crops and reduce supplies?

115 Lashof and Denvir, "Under New Guidance, 'Sustainable' Aviation Fuel in the US Could Be Anything But."

116 Anmar Frangoul, "Sustainable Jet Fuel Targets Could Push Food Prices Higher, Ryanair CEO O'Leary Warns," CNBC, October 21, 2021, https://www.cnbc.com/2021/10/21/ryanair-ceo-worried-about-sustainable-aviation-fuel-and-food-prices-.html.

117 Tyler Lark et al., "Environmental Outcomes of the US Renewable Fuel Standard," *Proceedings of the National Academy of Sciences* 119, no. 9 (March 2022).

118 Xin Zhao et al., "Estimating Induced Land Use Change Emissions for Sustainable Aviation Biofuel Pathways," *Science of The Total Environment* 779 (July 20, 2021): 4.

119 Natalie Stechyson, "Olive Oil Is How Much Now? Prices Jump — Again — amid Worldwide Shortage," *CBC News*, May 16, 2024, https://www.cbc.ca/news/business/olive-oil-price-1.7203884.

120 Statistics Canada, Table 18-10-0004-01.

121 Norman, "Feed Markets and the 'Big Oil Deficit.'"

- How much will purpose-grown energy crops such as grasses and trees compete for farmland, potentially displacing food crops and reducing supplies?

Despite these unknowns, in light of the potentially devastating impacts on the world's poorest families, it is prudent to assume a significant negative impact on food prices. Airlines now spend about $280 billion USD per year on fuel, globally.[122] Those airlines plan to double or triple air travel by mid-century. SAFs will be significantly higher in prices than conventional fossil-fuel Jet A. Thus, driven primarily by a plan to multiply air travel, airline expenditures on fuel may quadruple, or more, by mid-century—exceeding $1 trillion USD per year (in 2024 dollars). Granted, not all of that money will flow into food markets, but a significant amount will, either to purchase grain and oilseed feedstocks in the near term, or to purchase purpose-grown energy crops in the medium-term. Even a portion of that perhaps $1 trillion per year will exert upward pressure on food prices. Worse, as noted above, this food and land demand from SAFs will come atop other demands: to feed one or two billion more people; to expand dairy- and meat-heavy (and land-costly) diets to a growing global middle class; to produce additional land-sourced fibres and materials to replace petro-fibres and plastics, etc. Demands for food, fuel, fibre, and biomaterials from our farmland will increase dramatically in coming decades. Supplies will be constrained by efforts to hold land area, fertilizer use, and irrigation water use constant (or reduce the use of each). Rising demands intersecting with constrained supplies will mean increasing prices. SAFs are just one part of this equation, but unlike feeding people, SAFs are wholly *optional* uses of our farmland, especially because superior transportation alternatives exist (for those alternatives, see Ch. 20).

122 International Air Transport Association, "Industry Statistics: Fact Sheet."

12. SAFs and Justice

> "Globally, 1% of the world's population produces 50% of aviation emissions, while approximately 80% have never set foot on a plane."
> —Chapman, Mang, and Magdalena, "A Frequent Flying Levy in Europe...," 2024.[123]
>
> "Only a small minority of the global population will ever set foot on a plane, and even within the richest nations, most flights are taken by just a few people. When it comes to climate change, air travel is a uniquely damaging behaviour, resulting in more emissions per hour than any other activity [except] starting forest fires. ... It is also uniquely iniquitous. Everybody eats. But only the privileged few fly."
> —Hopkinson and Cairns, "Elite Status: Global Inequalities in Flying," 2021.[124]

About 4 percent of the global population take international air flights and *just 1 percent account for most of the miles in the air*.[125] The one or so percent of the global population that does most of the flying has a problem—large and rapidly growing GHG emissions from their preferred mode of travel. And this, in a world that must soon reach net-zero emissions. The solution to the problem faced by this one percent is SAFs. But those SAFs have impacts on 100 percent of people, including ecosystem damage and higher food prices. This last issue is one of justice. Everyone eats, but only a few fly. And if SAFs drive any significant land use competition (either for grains and oilseed production or the production of purpose-grown energy crops) then this can be seen as transferring land/wealth from poor food buyers to rich air travellers. Indeed, this is largely what is proposed, as airline trade groups speculate about growing SAF feedstocks for the traveling rich on the land in some of the world's poorest nations (see next chapter).

SAFs repurpose farmlands from food production, something that serves 100 percent of people, to aviation fuel production, something that serves a few percent. SAFs are yet another way that the world's richest people take for themselves an inordinate and unjust portion of the planet's resources.

Moreover, moving the sources for jet fuel from oil fields to farm fields will have the wholly predictable effect of accelerating land grabbing—undermining local ownership and control, local food production, and Food Sovereignty. The SAF project is one of global land colonization—imposing upon lands the new requirement to fuel business and vacation travel.

Further, in previous biofuel initiatives, one country could choose to produce such fuels and do so mostly using its own land, e.g., the US could produce ethanol from its corn acres but other nations could choose not to use their lands in these ways. But, because global air travel is a wholly integrated system, SAFs require a *global* project: production in most nations—production that may become increasingly mandatory as time goes on. The decision to pursue SAFs as an aviation decarbonization strategy is a de facto decision to require most nations to allocate some of their acres to fuel biomass production (see next chapter).

The brevity of this chapter should in no way indicate that this is a small issue: just the opposite. In a world soon to host 10 billion souls, and with hundreds of millions going to bed hungry today, and with millions dying for lack of food, the injustice of using foodland to fuel vacation jets may, indeed, be the largest and most grave issue touched on in this report. Many future reports and analyses must be written about these injustices, and the need for governments to ensure they are not complicit.

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123 Alex Chapman, Sebastian Mang, and Magdalena Heuwieser, "A Frequent Flying Levy in Europe: The Moral, Economic, and Legal Case" (London: New Economics Foundation and Stay Grounded Network, October 2024).

124 Lisa Hopkinson and Sally Cairns, "Elite Status: Global Inequalities in Flying" (Possible, March 2021).

125 Stefan Gössling and Andreas Humpe, "The Global Scale, Distribution and Growth of Aviation: Implications for Climate Change," *Global Environmental Change* 65 (November 1, 2020): 102194, https://doi.org/10.1016/j.gloenvcha.2020.102194.

13. SAFs and the Non-Rich World

> "SAF can generate economic benefits to all regions of the world, but especially developing nations, that have non-productive land for food crops which can be suitable for producing SAF feedstock."
> —Air Transport Action Group (ATAG), 2023.[126]

> "For many developing countries, SAF represents a significant economic and employment opportunity.... SAF can also provide economic benefits to parts of the world that have large amounts of land that qualifies as marginal, abandoned, or unviable for growing food, but is suitable for growing energy crops.... Many of these countries are developing nations that could benefit greatly from a new industry such as SAF production with the added benefit that it does not negatively impact their local food production and in some cases could actually strengthen the agricultural sector and improve food security for the region."
> —ATAG, 2023.[127]

An entire report could be written on the potential for SAFs to compete for land, undermine food availability, and raise prices in the poorest and most food-insecure nations. Here, we merely touch on these negative prospects. To get some sense of what might be happening or planned, we look briefly at Kenya.

Kenya Airways' Senior Manager of Innovation and Sustainability, Grace Vihenda, stated on a recent podcast regarding SAFs:

> "When it comes to bio-feedstocks, we have quite a bit, the weather is perfect and we have a lot of land for energy agriculture, which means if people want to plant, say, for example, castor or jatropha for bio-feedstocks.... To be truly sustainable in this journey of SAF, in my opinion, we have to set up locally, because there is everything we need to set up locally, and if the major manufacturers are not willing to do it, it doesn't mean we don't have capability in Kenya."[128]

Energy transnationals have also focused on Africa and countries such as Kenya as potential feedstock suppliers for biofuels, including SAFs. Italian oil company Eni supplied the biofuel for Kenya Airways first SAF-powered flight. According to one report:

> "Italian oil giant Eni ... has promised to create an entirely new supply chain of 'sustainable oils' from agricultural crops and has set up partnerships with six African countries in order to develop 'agri-hubs' that will supply vegetable oil for its refineries. The main crop that Eni is betting on, castor, is advertised as being drought-resistant and suitable for planting on poor quality land. In Kenya alone, Eni aims to enrol 400,000 farmers producing up to 200,000 tonnes a year by 2027."[129]

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126 Air Transport Action Group, "Beginner's Guide to Sustainable Aviation Fuel," 13.

127 Air Transport Action Group, "Beginner's Guide to Sustainable Aviation Fuel," 10.

128 Sustainability in the Air, "How Kenya Airways Plans to Unleash the Country's Untapped SAF Potential," accessed June 20, 2024, https://green.simpliflying.com/p/grace-vihenda-kenya-airways?publication_id=1539074&utm_campaign=email-post-title&r=2nfxf0&utm_medium=email.

129 "Uncovered: Italian Oil Giant's African Biofuels Gamble Falls Short," Transport & Environment, July 1, 2024, https://www.transportenvironment.org/articles/uncovered-italian-oil-giants-african-biofuels-gamble-falls-short-of-green-promises.

Eni and similar companies state that they plan to grow energy crops on "degraded, semi-arid or abandoned land that are not in competition with the food supply chain."[130] Many would wonder, though, why such acres could not instead be regenerated to grow food rather than energy crops?

Contrast the energy- and airline-industry plans for energy crop production, above, with these assessments of Kenyan food insecurity and hunger:

> "As parts of Somalia, Kenya and Ethiopia enter an expected sixth failed rainy season—the longest on record—and South Sudan, suffers a fifth consecutive year of severe flooding, 29 million people across the region are already experiencing severe hunger. In Kenya, data shows an unprecedented deterioration in the country's food security situation with the number of people facing severe hunger expected to rise by one million (from 4.4 million to 5.4 million) between March and June this year."
> —Oxfam, March 2023.[131]
>
> "Communities across Africa including in Kenya, Nigeria, Ethiopia, and Somalia are facing the worst food crisis seen in 40 years. ... Parents are being forced to skip meals so that their children can eat—sometimes not eating for days themselves. Children are being taken out of school to work to earn money, or to be sent to beg in nearby towns. According to the UN, 46 million people in Africa experienced hunger in the aftermath of the Covid-19 pandemic...."
> —British Red Cross, December 2023.[132]

In light of these assessments of human suffering—of hungry children begging so they can eat—who would not ask: if this "degraded" African land can grow castor or energy-crop grasses or trees, can it not grow fruit trees or berry bushes, pasture livestock, or in some way contribute to feeding people?

The bulk of SAF feedstocks from Kenya and elsewhere are shipped back to the EU and a significant part of the subsequent fuel is going to EU-based airlines.[133] African land is powering EU travel, not African.

The human population of the African continent is expected to be almost twice as large in 2050 as in 2020—2.5 billion people versus 1.4. In light of this, it seems unwise to assume that African lands can shoulder the added burden of producing fuel for vacation and business jets. Note also that Africa's most iconic species are firmly on the path to extinction: rhinos, tigers; lions; elephants; giraffes; leopards; cheetahs; and gorillas.[134] Thus, if there exists African land that is surplus to the need of feeding people, is jet-fuel production its best use? Will we prioritize flying over saving elephants and lions from oblivion?

This section is too brief to establish whether SAFs will undermine food security and increase starvation in the world's lowest-income regions, but the risks are large. These risks must be evaluated within the context outlined above: the massive quantities of biomass feedstocks (grains and oilseeds, energy crops, and/or crop residues) seemingly needed from the planet's croplands. Many SAF producers point to used cooking oil, agricultural "wastes," and other seemingly benign feedstocks; they point to using only non-agricultural or "abandoned" land, so as not to compete with food production; but sophisticated observers of global energy and food markets will feel immediate concerns as to how multi-billion-dollar aviation and energy industries, desperate for billions of tonnes of SAF feedstocks, may govern themselves amid poor farmers and other citizens in places such as Africa, Asia, and South America.

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130 Eni SpA, "Our Activities in Kenya," accessed July 1, 2024, https://www.eni.com/en-IT/actions/global-activities/kenya.html.

131 "Hunger Soars in East Africa as Sweeping Aid Cuts and Another Failed Rainy Season Looms," Oxfam GB, March 27, 2023, https://www.oxfam.org.uk/media/press-releases/hunger-soars-in-east-africa-as-sweeping-aid-cuts-and-another-failed-rainy-season-looms/.

132 "Africa Food Crisis: More Than 150 Million People Are Going Hungry," British Red Cross, accessed June 20, 2024, https://www.redcross.org.uk/stories/disasters-and-emergencies/world/africa-hunger-crisis-100-million-struggling-to-eat.

133 "From Farm to Fuel: Inside Eni's African Biofuels Gamble," Transport & Environment, July 1, 2024, https://www.transportenvironment.org/articles/from-farm-to-fuel-inside-enis-african-biofuels-gamble.

134 Franck Courchamp et al., "The Paradoxical Extinction of the Most Charismatic Animals," *PLOS Biology* 16, no. 4 (April 12, 2018): e2003997, https://doi.org/10.1371/journal.pbio.2003997.

14. SAFs and Competition for Clean Energy and Green Hydrogen

> "low-carbon electricity generation ... is an absolute requirement for aviation to reach net zero CO_2 emissions by 2050. ... Making alternative aviation fuels could increase the industry's electricity demand by up to 10,000 TWh (36EJ) by 2050, *adding roughly the equivalent of half of all electricity produced globally in 2021*..." [italics added].
> —International Air Transport Association (IATA), 2023.[135]

> "Aviation could require in excess of 100 million tonnes of hydrogen by 2050 (about as much as the whole global hydrogen production today).... Furthermore, about 99% of all hydrogen used today is not green.... The scaling-up of green hydrogen production from this very low base is absolutely necessary for aviation to reach its net zero goals...."
> —International Air Transport Association (IATA), 2023.[136]

> "The central problem is that a number of these feedstocks have other potential markets. ... Hydrogen, a key input into advanced biofuels conversions processes and most importantly power-to-liquids, has many potential downstream markets in the power sector, transportation sector, and heavy industry. There will be competition for the lowest carbon hydrogen, which SAF producers will need...."
> —Canadian Council on Sustainable Aviation Fuel (C-SAF), 2023.[137]

> "There is, however, an opportunity cost in devoting clean energy resources to decarbonizing aviation when these limited resources could be deployed to decarbonize other, more essential sectors through less energy-intensive means...."
> —Institute for Policy Studies and Inequality.org, 2024.[138]

The net-zero-by-2050 aviation project requires huge amounts of clean solar and wind electricity and huge amounts of zero-emission green hydrogen—quantities of clean electricity and green hydrogen that are *multiples* of current global production. Thus, decarbonizing aviation via SAFs will require a large build-out of these electricity and hydrogen supplies. But so, too, will the decarbonization of everything else. The large demands from aviation for clean energy and green hydrogen will come atop, and *be in competition with*, large demands for electricity and hydrogen to decarbonize home heating, industry, other forms of transport, and even just the existing electricity grid. For *many decades* to come, supplies of clean electricity and green hydrogen will continue to fall short of potential needs. Thus, it is prudent to ask: On top of the home-heating decarbonization megaproject, the electrify-all-the-cars-with-clean-electricity megaproject, the decarbonize heavy industry megaproject, etc. should we add the SAFs megaproject? To put it another way, is it not likely that by adding yet another huge demand source for energy and hydrogen we will delay decarbonization elsewhere? Will SAFs lead to emissions reduction? ...or emissions *shifting*? ...as ambitious decarbonization of the aviation sector slows decarbonization elsewhere as a result of constrained resources to produce the needed clean energies and green fuels?

SAFs and clean electricity

Net-zero global GHG emissions by 2050 is an *ambitious* goal. Properly understood, it requires near-wartime levels of activity. For the global electricity system, we are, in effect, planning to:

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135 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 2.
136 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 2.
137 Allan, Goldman, and Tauvette, "The C-SAF Roadmap: Building a Feedstocks-to-Fuels SAF Supply Chain in Canada," 46.
138 Kalena Thomhave, Omar Ocampo, and Chuck Collins, "Greenwashing the Skies: How the Private Jet Lobby Uses 'Sustainable Aviation Fuels' as a Marketing Ploy" (Washington, DC: Institute for Policy Studies and Inequality.org, May 2024), 12.

1. Decarbonize current electricity generation by replacing remaining fossil-fuelled power-stations (coal and natural gas) with clean, renewable options such as solar and wind;

2. Transfer the home-heating energy load from fossil fuels such as natural gas to electricity via the installation of heat pumps and similar technologies;

3. Transfer the light-vehicle energy load from gasoline and diesel fuel to electricity via EVs;

4. Probably transfer the energy load for heavy trucks to electricity, too;

5. Transfer much of the energy load for industry from natural gas and coal to clean electricity;

6. Add large amounts of capacity to power artificial intelligence (AI) data centres;

7. Install still more clean generating capacity to make green hydrogen (see next section); and

8. Add another large increment of clean-energy-generating capacity to supply a larger global population (billions more people) and a growing economy. (In the 20th century, the global economy grew sixteenfold! It will grow less in the 21st, but still by a multiple.)

To accomplish all the preceding, we must multiply our overall electricity generating capacity; increase our clean energy generating capacity by an even larger multiple; and increase the capacity of our distribution grids, perhaps by a multiple. In the face of these daunting tasks, is it wise to blithely add to our "to do" list yet another green-energy megaproject? Is it reasonable to assume we can accomplish all the above and also create enough additional surplus capacity to produce a large portion of the SAFs needed for a doubled or tripled air-travel sector? Recall: "Making alternative aviation fuels could [require] ... adding roughly the equivalent of half of all electricity produced globally in 2021."

Here is a bracing assessment from the United States Department of Energy (US DOE):

> "E-fuels by their nature will be reliant on the accessibility of abundant, very low-cost, and low-carbon electricity and/or hydrogen produced from sources such as wind, solar, hydropower, and nuclear. With an energy intensity on the order of about 100 kWh/gal e-SAF, moving forward, one of the greatest enablers to producing SAF will be the rapid and sustained build-out of renewable electricity infrastructure.... If the 35-billion-gal/yr [U.S. 2050] target were met entirely with e-fuels, estimates show that nearly 3,500 TWh of electricity would be required, *representing a more than 5-times increase from current wind and solar generation levels*.... Hitting 35 billion gallons of SAF per year would draw significantly from domestic low-carbon resources and likely *face competition from a variety of other use cases*" [italics added].[139]

Just to produce Electro-SAFs, the US may have to increase its solar and wind generating capacity *five-fold*. Again, this comes atop demands for clean energy to decarbonize heating, industry, and transport.

SAFs and green hydrogen

Even more than clean energy, supplies of green hydrogen will be in short supply. IATA projects 2045 demand for green hydrogen at nearly 100 million tonnes annually.[140] Current production of low-emission ("blue") and zero-emission ("green") hydrogen is just 1–2 million tonnes annually[141]—implying

139 Grim et al., "The Challenge Ahead," 8.
140 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 3.
141 International Energy Agency, "Global Hydrogen Review 2023" (IEA, 2023), 13.

the need for a fifty-fold scale-up, *just for aviation*. And this massive increase in demand for hydrogen for aviation will come alongside similar multiplications in demand from many industries and economic sectors which are counting on green hydrogen supplies to solve their emission problems.

Given this massive projected reliance on hydrogen, a couple things to consider:

1. Green hydrogen is energy inefficient. If we use clean electricity directly, in an EV or train or factory motor, the usable work from that device is probably about 90 percent efficient—90 percent of the energy in the electricity comes out as usable work and only 10 percent is lost as heat and noise. But if we turn that green electricity into hydrogen and then convert that hydrogen back into electricity in a fuel cell (perhaps in a bus or train) overall system efficiency is much lower. And it is much lower still if we turn it into liquid or gaseous fuel and then combust it, as there are very large heat losses; and

2. It will take a massive scale-up of green hydrogen just to decarbonize *current* hydrogen uses. One of the largest uses is nitrogen fertilizer production. Nearly all that production uses grey hydrogen—from fossil fuels with attendant GHG emissions. Merely decarbonizing *existing* hydrogen uses will probably demand all foreseeable green hydrogen scale-up for many years to come—perhaps decades. If we are severely challenged to decarbonize *existing* hydrogen uses, there simply will not be any new green hydrogen available for novel uses, such as SAFs.

That last point means that until we decarbonize existing hydrogen uses, it is premature to imagine adding new demands. To do so, amid very constrained supplies of green hydrogen, will simply delay decarbonization elsewhere. If using more green hydrogen for SAFs production means less green hydrogen for fertilizer production we have emissions shifting, not emissions reduction. Figure 15, right-hand side, shows the many sectors that may want to rely on green hydrogen for decarbonization.

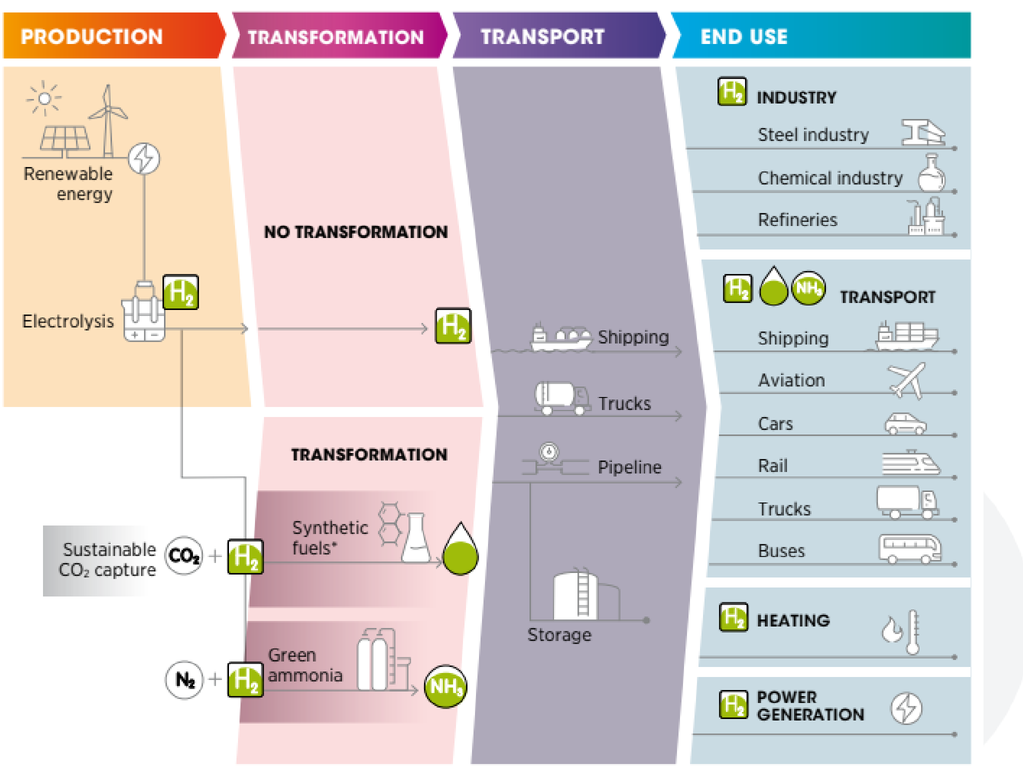

Figure 15. Projected end-uses for green hydrogen.
Source: Reproduced from International Renewable Energy Agency (IRENA).[142]

142 International Renewable Energy Agency, "Green Hydrogen: A Guide to Policy Making" (Abu Dhabi: IRENA, 2020).

Note that both the aviation sector *and* the ocean-shipping sector may vie for green hydrogen.

> "Strategic developments in the [ocean] shipping and aviation sector should be in line with the objectives of reducing carbon emissions.... But huge efforts are needed to achieve a zero-carbon emission of both transport sectors because, given the estimations of the International Energy Agency, aviation sector requires about 220 Mton/year of biofuel oil equivalents to fully decarbonized, while ... the case of shipping sector is a little bit higher, amounting to 240 Mton/year of oil equivalents...."[143]

Thus, to the quantities of hydrogen and other feedstocks needed to decarbonize aviation, there may be an added demand, just as large, to decarbonize ocean shipping. And if heavy trucking cannot be decarbonized with battery-electric vehicles, that sector may also require comparable amounts of hydrogen. And it remains unclear whether we will electrify freight trains or whether those, too, will attempt to rely on hydrogen.

With low-emission (blue and green) hydrogen production effectively at zero today, is it reasonable to assert that multiple economic sectors can simultaneously and successfully scale up hydrogen production to decarbonize fertilizer production, aviation, ocean shipping, trucking, heavy industry, building heating, and a range of other uses? Are those who point to hydrogen as a decarbonization solution deceiving themselves? ...or us?

The colours of hydrogen

Grey hydrogen (H), most common now, is made from natural gas (CH_4), and the excess carbon (C) is released into the atmosphere as carbon dioxide (CO_2); Blue hydrogen is produced similarly, but much of the CO_2 is captured and not released; Green hydrogen is produced without GHG emissions, often by using renewable electricity from solar panels or wind turbines to split water (H_2O) via electrolysis into hydrogen (H) and oxygen (O_2).

Competition for clean energy and green hydrogen: conclusion

Ambitious efforts to reduce emissions from business-travel and vacation jets may slow emissions reduction in other sectors. There is only so much green hydrogen, clean electricity, farmland area, and harvestable biomass to go around; well past 2050, there will be too little. Commenting on SAFs, one analyst notes that "To bring these fuels to the scale needed would ... take resources away from more urgent decarbonization priorities."[144]

This is an especially crucial issue as the SAF megaproject is an *energy hog*—requiring *huge* quantities of energy and energy-derived hydrogen. SAFs require so much energy, partly because of their inherent inefficiencies. As this report details below, within the bounds of continents, trains provide a more feasible and much more energy-efficient option. Moving the same number of passengers the same distance on trains requires a fraction of the energy. As we move into a future of rapidly rising clean-energy demands and constrained supplies, choosing options that minimize overall energy requirements is key to success. SAFs fail this test.

Here is an assessment from the U.S. Department of Energy:

143 Ana Arias et al., "Assessing the Future Prospects of Emerging Technologies for Shipping and Aviation Biofuels: A Critical Review," *Renewable and Sustainable Energy Reviews* 197 (June 1, 2024): 3.
144 Milman, "'Magical Thinking.'"

> "Demand for jet fuel [is] expected to more than double by 2050 and triple by 2070.... However, with the demand for sustainable carbon resources anticipated to rise sharply in the coming decades across multiple other use cases (green chemicals, biohydrogen, bioenergy plus carbon capture, biomethanol, and other strategic fuels including marine and renewable diesel), there is some concern that as competition for this limited resource grows, it could impact the ability to wholly satisfy the projected sharp rise in demand for SAF."[145]

To conclude this section, a systems-thinking assessment from a 2023 science journal article:

> "This paper examines aviation decarbonisation roadmaps from a system perspective. Clearly, the societal goal is not to achieve 'net zero' of one single sector, but to maximise our chances of averting catastrophic climate impacts.... If decarbonising one sector undermines the opportunity of transitioning other parts of the global socio-economic system, then questions need to be asked as to how allocation of scarce resources (here, land and clean energy) should be prioritised. Understanding the consequences of one sector's climate action on the ability to achieve collective mitigation goals is crucial. ... The real-world availability of clean primary energy at present and for the foreseeable future is limited. In terms of achieving global decarbonization, clean energy, just like land, represents a scarce resource. SAF is only one amongst many potential uses."[146]

Especially relevant to the BECCS vs SAFs trade-off, that journal article goes on to note the "opportunity costs" of SAFs, i.e., the things we won't be able to accomplish if we prioritize SAFs. It states: "Every unit of biomass or electricity dedicated to SAF is lost to other uses. Consuming electricity to produce e-kerosene represents a major opportunity cost of decarbonising other sectors, including the electricity sector itself."

145 Grim et al., "The Challenge Ahead," 1–2.
146 Becken, Mackey, and Lee, "Implications of Preferential Access to Land and Clean Energy for Sustainable Aviation Fuels," 2–3.

15. Agricultural Emissions and SAFs

The aviation sector wants to make very significant progress toward net zero by 2050. But so does the agricultural sector. And even as farmers and governments struggle to reduce agricultural emissions, the SAF megaproject will almost certainly drive them up!

SAFs may require increased crop output (for the portion derived from grains and oilseeds); increased removals and deliveries of crop residue biomass (straw, corn stover, husks, chaff, etc.); and additional land planted to purpose-grown energy crops. The impacts on agricultural emissions include:

1. **More fertilizer use and attendant emissions.** Increased production of crops—either energy crops or grain and oilseed crops—will require more fertilizer. In addition, the removal of crop residue biomass will also remove nitrogen, phosphorus, and potassium nutrients, again requiring additional synthetic fertilizers to replace a portion of the tonnage removed. Increased fertilizer use will increase agricultural emissions, both in the production of those fertilizers and, in the case of nitrogen, from in-field GHG emissions.

2. **Lower rates of soil carbon sequestration.** As currently modeled in Canada's National Inventory Report (NIR), soil carbon changes are a function of "the change in crop productivity/crop residue C input to soils...." Soil carbon sequestration is, to a significant extent, a function of the crop residue carbon inputs going into the soil, i.e., sequestration is a direct function of the amount of residue left on the land. Removing residues will slow or reverse sequestration. For additional details and citations, see Chapter 4, above, on Bio-SAF {residues}.

Thus, reductions in aviation emissions may be partly offset by increases in agricultural emissions, driving up the latter and moving farmers further away from net zero. Again, we see *emissions shifting*.

Canadian agricultural emissions are up by 39 percent over the past 32 years. There is a concerted push to bend that trendline down. Canadian taxpayers are providing hundreds-of-millions of dollars per year to farmers via incentives and cost-shared programs to spur emission reductions. But as one Saskatchewan farmer noted, a biofuels megaproject and the amounts of added fertilizer any such project implies will veto agricultural emissions reduction.[147]

It is impossible that the Earth can supply the added quantities of grains, oilseeds, residue biomass, and purpose-grown energy crops without significantly increased quantities of fertilizers. And it is probably impossible that removing billions of tonnes of carbon-rich biomass each year—for BECCS and SAFs—can be accomplished without slowing or reversing soil carbon sequestration. The overall effect will be to drive agricultural emissions up. As this occurs, farmers risk finding themselves alone, mid-century, as one of the few sectors with very high and rising GHG emissions. Such a situation would place the agricultural sector under increasing scrutiny and criticism—raising the spectre of intrusive regulation to force rising agricultural emissions to fall.

Farmers should think carefully before supporting a project that will lower emissions from aviation while raising emissions from agriculture.

Again, though this report focuses on aviation fuels, many of the points made here will apply to any sector or industry that intends to draw massively on biomass for fuels or materials. The adverse effects on farmers' sequestration efforts or GHG emissions can be triggered, not only by SAFs, but also by similar potential biofuel megaprojects for ocean shipping, railways, or heavy trucking; by BECCS; and even, though to a lesser extent, by biomaterials projects to replace plastics and petro-textiles.

147 Personal conversation with Bladworth-area farmer Ian McCreary, 2022.

16. SAFs and Zero Emissions

Above, this report details the challenges and negative impacts of the ambitious proposal to shift the energy supply for the world's jets to the planet's land base and renewable electricity supply. Those challenges and impacts might be acceptable costs if SAFs decarbonized aviation, but SAFs will not. Even in most best-case scenarios, emissions continue and warming effects could *increase*.

Many SAFs won't deliver zero emissions

Near-term SAFs from corn, soy, and canola certainly are not zero-emission fuels. Even the later fuels from purpose-grown energy crops will not be zero-emission in many cases, as these will require fertilizers, tractor fuels, transport fuels, etc.[148]

Moreover, most studies project that SAFs will continue to be blended with fossil-fuels. A selection of studies from IATA, ICAO, and others project that about 30 percent of aviation fuel in 2050 will still come from fossil fuels.[149] Transport Canada projects that, for this country, "roughly 70 percent of fuel used by 2050 would be SAF" and the remainder fossil fuels.[150]

The International Air Transport Association (IATA) 2023 *Roadmap* summarized results from a dozen reports that estimated emissions in 2050, with more than half the reports projecting CO_2 emissions above 116 million tonnes per year and ranging as high as 465 million tonnes (the latter being approximately 60 percent of current global aviation emissions tonnage).[151]

Net zero is not zero

For the next several decades, jets will continue to create emissions from fossil fuels and from SAFs. And although emissions per flight or per passenger-kilometre may fall, the planned doubling of flights and passenger kilometres means that even with near-best-case SAF rollout, emissions a decade or two from now may be little changed from those today. Figure 16 shows a scenario for Canada.

148 CORSIA models some energy crops as having negative emissions due to the assertion of very rapid soil carbon increases. In a Canadian context such scenarios seem unlikely. The NFU does not, at this time, accept the modelled values for negative emissions. More scrutiny is needed on these extreme claims. Moreover, all soils trend toward maximum soil carbon levels—equilibrium or saturation levels. Thus, even if some very degraded and low-carbon soils could register very rapid carbon gains, over time those gains would slow to zero. Again, very significant critical analysis is needed before policymakers and farmers accept claims of carbon-negative SAF feedstocks.

149 International Air Transport Association et al., "Aviation Net-Zero CO2 Transition Pathways: Comparative Review," tbl. 4.

150 Transport Canada, "Canada's Aviation Climate Action Plan: 2022-2030" (Ottawa: Government of Canada, 2022), 11, https://www.icao.int/environmental-protection/Documents/ActionPlan/CANADAs-AVIATION-CLIMATE-ACTION-PLAN-2022-2030.pdf.

151 International Air Transport Association et al., "Aviation Net-Zero CO2 Transition Pathways: Comparative Review," tbl. 4.

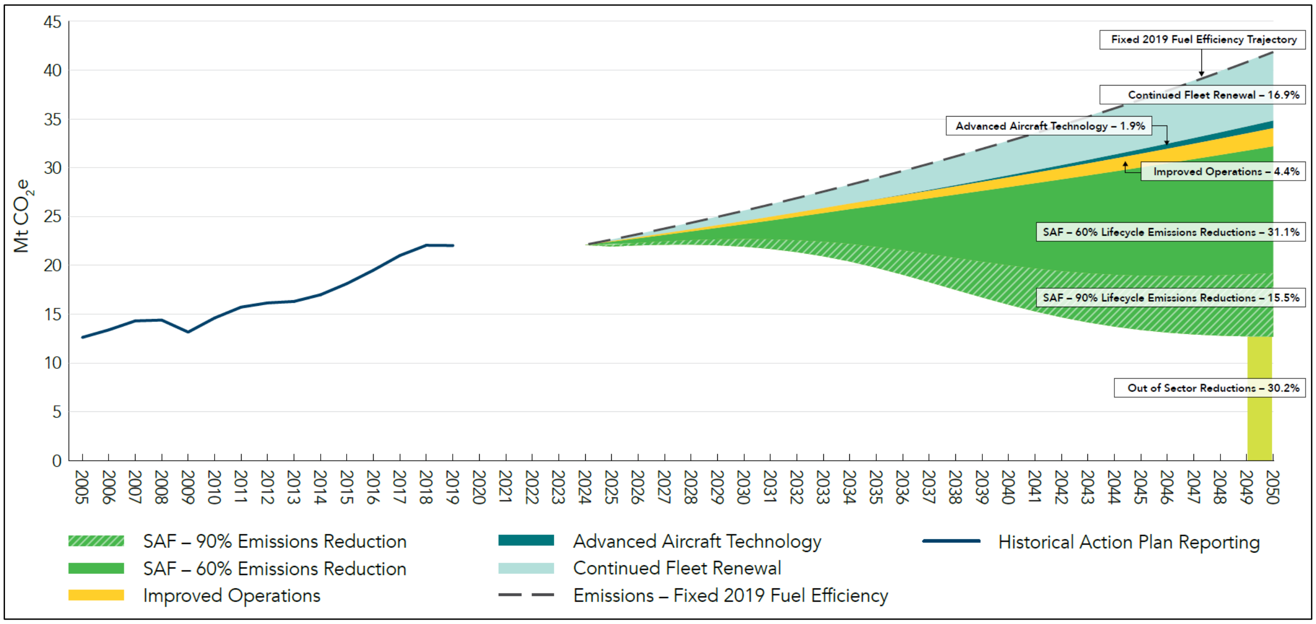

Figure 16. Canadian aviation emissions—a scenario to 2050.
Source: Reprinted from Transport Canada, "Canada's Aviation Climate Action Plan: 2022–2030."[152]

In this scenario, actual GHG emissions for Canadian aviation in 2050 are 12–13 million tonnes per year—about the same as in 2005, and roughly 60 percent of current emissions. Because SAFs themselves create emissions and because a projected 30 percent of aviation fuel will still come from fossil fuels in 2050 and because flight volumes are on track to double, not surprising, SAFs do not deliver on the goal of zero emissions. Rather, when combined with rapidly rising utilization, SAFs are projected to deliver about a 40 percent reduction by 2050. In reality, the aviation industry does not have a plan for net-zero.

Offsets

Note the bottom category on the right-hand side of Figure 16: "Out of Sector Reductions." This means emission offset schemes, emissions trading, and carbon markets. Transport Canada explains:

> "The Action Plan forecast suggests at minimum 12Mt of emissions would need to be offset in 2050. ... Fortunately, a key element of the net-zero emissions concept is that emissions do not need to reach zero for each discrete human activity and sector. For a sector to be net-zero, the GHG being released into the atmosphere must be balanced by reductions or removals from actions taken elsewhere. ... Out-of-sector emissions reductions must be achieved as a result of actions (e.g., investments or projects) that generate high quality offset credits, from GHG emission reduction or removal projects, such as biological sequestration and technology-based projects such as direct air capture and sequestration. Given that the Action Plan forecast that 12Mt of ... offsets will be required by 2050, this impl[ies] that substantial investments in GHG emission reduction and removal projects will be required."[153]

Similarly, airline trade group IATA tells us that: "To achieve net zero in 2050, almost all the global roadmaps suggest that the aviation sector will need help from market-based measures and carbon removals to bridge the gap (ranging from 95 $MtCO_2$ to 370 $MtCO_2$) between their residual emissions and net zero emissions in 2050."[154]

152 Transport Canada, "Canada's Aviation Climate Action Plan: 2022-2030," 10.
153 Transport Canada, "Canada's Aviation Climate Action Plan: 2022-2030," 24.
154 International Air Transport Association et al., "Aviation Net-Zero CO2 Transition Pathways: Comparative Review," 1.

Entire reports could be written about voluntary offsets, emissions trading, and carbon markets. Here, suffice to note the very sketchy past performance of voluntary offset schemes[155] and to flag the fact that, in the future, the number of sectors looking to buy their way out of emissions problems via offsets will almost certainly create more demand than can be met by any supply of credible offsets.

Zero GHGs ≠ zero warming

The operations of jet aircraft warm the planet in multiple ways. GHG emissions such as CO_2 from fuel combustion is one way, but non-CO_2 effects appear to be *even large*r. Fossil fuel CO_2 may be contributing less than half the warming effects from jet aviation, and other effects such as condensation trails (and resulting cirrus clouds) and nitrogen-oxides (NO_x) are calculated to produce half to two-thirds of the total warming effect.[156]

A 2024 peer-reviewed article in the journal *Atmospheric Chemistry and Physics* tells us that:

> "Aviation's cumulative CO_2 emissions account for one-third of its overall effective radiative forcing (ERF), while the remaining two-thirds are estimated to arise from non-CO_2 components such as contrail cirrus, nitrogen oxides (NO_x), particulate matter, and stratospheric water vapour emissions."[157]

The condensation-trail warming effects of aircraft can be reduced by changing flightpaths and times. Some airlines are examining steps to reduce warming effects in these ways. Also, some initial research indicates that some SAFs may reduce condensation trail clouds and related warming.[158] But even if all such positive measures are taken, and the contributions of condensation trail cloud formation and nitrogen oxide effects are reduced, SAF-powered flights will still have very significant warming effects. And, given industry plans to double or triple flight numbers by mid-century, even very significant reductions in per-flight condensation-cloud-related warming will likely leave overall warming effects higher, not lower, by mid-century.

155 Patrick Greenfield, "Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Certifier Are Worthless, Analysis Shows," *The Guardian*, January 18, 2023, sec. Environment, https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe; Patrick Greenfield, "'Reform or Go out of Business,' Carbon Offsetting Industry Told," *The Guardian*, June 26, 2024, sec. Environment, https://www.theguardian.com/environment/article/2024/jun/26/voluntary-carbon-market-offsetting-industry-reforms-cccg-climate-crisis-advisory-group-aoe; Patrick Greenfield, "Carbon Credit Speculators Could Lose Billions as Offsets Deemed Worthless," *The Guardian*, August 24, 2023, sec. Environment, https://www.theguardian.com/environment/2023/aug/24/carbon-credit-speculators-could-lose-billions-as-offsets-deemed-worthless-aoe; Patrick Greenfield, "Market Value of Carbon Offsets Drops 61%, Report Finds," *The Guardian*, May 31, 2024, sec. Environment, https://www.theguardian.com/environment/article/2024/may/31/market-value-of-carbon-offsets-drops-61-aoe; Nina Lakhani, "Revealed: Top Carbon Offset Projects May Not Cut Planet-Heating Emissions," *The Guardian*, September 19, 2023, sec. Environment, https://www.theguardian.com/environment/2023/sep/19/do-carbon-credit-reduce-emissions-greenhouse-gases; Nina Lakhani, "Corporations Invested in Carbon Offsets That Were 'Likely Junk', Analysis Says," *The Guardian*, May 30, 2024, sec. Environment, https://www.theguardian.com/environment/article/2024/may/30/corporate-carbon-offsets-credits.

156 David Simon Lee et al., "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018," *Atmospheric Environment* 244 (January 1, 2021); Roger Teoh et al., "Global Aviation Contrail Climate Effects from 2019 to 2021," *Atmospheric Chemistry and Physics* 24, no. 10 (May 27, 2024).

157 Teoh et al., "Global Aviation Contrail Climate Effects from 2019 to 2021," 6071.

158 Raphael Satoru Märkl et al., "Powering Aircraft with 100% Sustainable Aviation Fuel Reduces Ice Crystals in Contrails," *Atmospheric Chemistry and Physics* 24, no. 6 (March 27, 2024): 3813–37, https://doi.org/10.5194/acp-24-3813-2024.

17. Taxpayer Subsidies (to Reduce the Cost of Flying)

> "Role of governments: To develop policies that efficiently accelerate the commercial production and deployment of SAF. Positive, supply-side incentives are the most effective policy tool and involve the allocation of public funds...."
> —International Air Transport Association (IATA), 2023.[159]
>
> "Today in Manitoba, we announced a significant investment to seize global economic opportunities and help position Manitoba and Canada as leaders in the future of Sustainable Aviation Fuel production."
> —Honourable Jonathan Wilkinson, Minister of Energy and Natural Resources, 2024.[160]
>
> "Launched in June 2021, [Canada's] Clean Fuels Fund aims to invest $1.5 billion to grow the production of clean fuels in Canada, such as hydrogen, biofuels and synthetic fuels."
> —Government of Canada news release, 2024.[161]
>
> "We calculate the transition cost of SAF use ... [as] an annual average transition cost of USD 174 billion, though it rises from USD 1 billion in 2025 to a rather eye-watering USD 744 billion in 2050. Our forecast for the net profits of the airline industry in 2024 is USD 30 billion.... Putting the transition cost in perspective in this way should *make it blatantly clear that policy support is urgently required* to bring the cost of the transition solutions down and to minimize their premium over fossil fuels. ... The challenge of meeting the financial needs of the net zero transition by the air transport industry itself becomes *impossible without policy support*" [italics added].
> —International Air Transport Association (IATA), 2024.[162]
>
> "The landmark [US] IRA [*Inflation Reduction Act*] ... raises SAF support under the blender's tax credit (BTC) to provide $1.25–$1.75 per gallon of SAF...."
> —World Economic Forum, 2024.[163]
>
> "Currently, unsubsidized (e,g, without any government or state incentives) SAF trades at a substantial premium compared to conventional jet fuel, typically costing 2–5 times more."
> —Simpliflying, 2024.[164]
>
> "Air transport's net zero CO_2 emissions goal is ... critically dependent upon policy makers' concerted efforts to make it happen."
> —International Air Transport Association (IATA), 2024.[165]

All SAFs are more expensive than fossil fuel Jet A; Electro-SAFs are especially expensive. IATA projects that even after dramatic cost decreases over the next two decades, in 2050, all major SAF types will be two to three times more expensive than the projected long-term average price of fossil fuel Jet A.[166]

As we explore below (see chapter 18 on Scaling Up) the airline industry's SAF transition will cost trillions. The industry's solution to this cost problem is to use taxpayer money to keep flying affordable. But these

159 International Air Transport Association, "Net Zero 2050: Sustainable Aviation Fuels," 2.
160 Canada, "Minister Wilkinson Announces Over $6 Million to Unlock Sustainable Aviation Fuel Production in Manitoba."
161 Canada, "Minister Wilkinson Announces Over $6 Million to Unlock Sustainable Aviation Fuel Production in Manitoba."
162 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 1 & 28.
163 World Economic Forum and Kearney, "Scaling Up Sustainable Aviation Fuel Supply: Overcoming Barriers in Europe, the US and the Middle East" (World Economic Forum, March 2024), 18, https://www3.weforum.org/docs/WEF_Scaling_Sustainable_Aviation_Fuel_Supply_2024.pdf.
164 SimpliFlying and Sustainable Aviation Futures, "Pathways to Sustainable Aviation Fuel: North American Edition," 43.
165 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 1.
166 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 23.

subsidies, in effect, transfer money from the large percentage of citizens who pay taxes to the small percentage who do most of the flying, to the corporations who utilize business travel, to airlines and fuel makers, and to the shareholders of those corporations.

Airlines and their trade associations assert that once we get past an initial roll-out phase, the cost of SAFs will fall and become competitive and that subsidies will no longer be needed. It is worth asking whether this is likely. Given that SAFs will be in short supply for decades (again, the Scale-Up Problem, next chapter), demands exceeding supplies would seem to imply continued elevated prices. And given airlines' ongoing strategies to continue to double and redouble the amount of flying they do, they seem intent on driving demand higher and higher and higher. It is very likely that supply and demand imbalances will mean that SAFs will be high-cost well through the second half of this century.

Before governments and their taxpayer dollars get drawn into a multi-decade, multi-trillion dollar scheme, those governments should ponder the justice implications of subsidizing flying, the opportunity costs of pouring hundreds-of-billions of taxpayer dollars into aviation rather than alternative transport systems, the negative effects of SAFs listed in this report and elsewhere, and the significant chance that the SAF megaproject will fail—not only missing its own decarbonization timelines and targets but also causing (via competition for resources) other sectors to miss theirs.

Let us conclude with one final variation on the quotes that began this chapter—the airline industry's self-assessment of its financial challenges and risks:

> "Relating the projected transition costs [an average of 232.8 billion per year] to the profitability of the airline industry, we obtain a measure of the size of the challenge. In 2024, the net profit of the air transport industry is estimated to reach USD 30.5 billion.... Awareness of these numbers ought to make it unambiguously clear to all that *policy measures are urgently needed to bring the SAF MSPs [minimum selling prices] down to levels that airlines can conceivably pay and still remain in business*" [italics added].[167]

The annual average cost of the SAF transition is roughly 8 times the total annual profits of the airline industry: $232.8 billion vs $30.5. SAF costs create the risk that airlines may not be able to "remain in business." The major airlines and aircraft makers are admitting that, in the face of the planetary net-zero imperative, they are insolvent. Before democratic governments get sucked into this multi-trillion-dollar vortex and begin flowing thousands of dollars per taxpaying-family to airline shareholders, it is absolutely crucial that governments initiate a broad democratic consultation and that all involved completely understand the full implications of the SAF megaproject and the opportunity costs of putting our limited financial, energy, and other resources into this speculative plan.

Unless taxpayers cover many of the costs, the SAF transition cannot happen. A thorough democratic discussion is needed before we commit to this path. It is arrogant and undemocratic for airlines to simply assume that citizens want to pay the costs of the SAF transition.

167 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 29.

18. The Scale-Up Problem

"SAF production needs to be expanded exponentially."
—USDA, US EPA, US DOT, US DOE, 2022.[168]

"Aviation's decarbonization depends critically upon the significant scale-up of SAF production—by a factor of 1,000 between 2023 and 2050."
—International Air Transport Association (IATA), 2024.[169]

"[Net zero aviation] will require close to 7,000 SAF bio-refineries by 2050. More than 700 million tonnes of CO_2 will need to be extracted from the atmosphere in 2050 with carbon capture technologies, either to produce SAF, or for permanent carbon removals. The largest projects in the pipeline today are planning on delivering a carbon dioxide removal capacity of 0.5–1 million tonnes per year, showing the scale of the challenge ahead. Over 100 million tonnes of low-carbon hydrogen will also be needed, mostly for the production of SAF...."
—International Air Transport Association (IATA), 2023.[170]

"The vast majority of technologies related to the aviation net zero transition are currently in the R&D stage."
—International Air Transport Association (IATA), 2023.[171]

"As things stand there is not going to be enough SAF to meet our goal of Net Zero 2050. *Production will need to be scaled up 80 or 100 times even to reach 10 [percent] SAF by 2030*, and that requires urgent government action" [italics added].
—Holly Boyd-Boland, Virgin Atlantic airline's VP for corporate development, 2024.[172]

"From now 'til 2050, you need an almost 1,000-times increase in the production of SAF.... And if you break that in terms of plant size of average of 50-70,000 tonnes per annum, you need almost 300 plants per year."
— Preeti Jain, IATA, Head of Net Zero Transition Program, 2024.[173]

Worldwide, in 2023, SAFs production tripled to 600 million liters, representing 0.2 percent of global jet fuel use[174] and approximately 0.1 percent of projected 2050 demand for SAFs. Thus, SAF production must be scaled up 500- to 1,000-fold in just 26 years.

Looking at the US situation, the USDA, EPA, DOT, and DOE offer this bracing assessment of US supply challenges: "Going from 5 million to 3 billion gal/yr by 2030 is a 600-fold increase that requires a 122% year-over-year growth in production to 2030. ... More than 400 biorefineries and 1 billion tons of biomass and/or gaseous carbon oxide feedstock will be needed to produce 35 billion gal/yr by 2050."[175]

168 U.S. Department of Energy et al., "SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel," 18.
169 International Air Transport Association, "SAF Handbook," 30.
170 International Air Transport Association, "Energy and New Fuels Infrastructure: Net Zero Roadmap," 8.
171 International Air Transport Association, "Finance: Net Zero Roadmap" (Montreal: IATA, June 4, 2023), 6, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/finance-net-zero-roadmap.pdf.
172 Christopher Jasper, "Why Aviation Chiefs Fear Net Zero Could Cripple Air Travel," *The Telegraph*, June 2, 2024, https://www.telegraph.co.uk/business/2024/06/02/why-aviation-chiefs-fear-net-zero-could-cripple-air-travel/.
173 "IATA's Blueprint for Accelerating SAF Production and Adoption," Sustainability in the Air, June 6, 2024, accessed July 5, 2024, https://open.spotify.com/episode/1k06nE6EljXBhHgOfTOdnh.
174 International Air Transport Association, "Net Zero 2050: Sustainable Aviation Fuels," 2.
175 U.S. Department of Energy et al., "SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel," 3.

Such a dramatic and rapid scale-up will be costly. According to IATA: "Several reports have analyzed the investment required to achieve the air transport industry's goal of reaching net zero CO_2 emissions.... The investments required to be undertaken in the 27-year period (2023-2050) amount up to USD 5.3 trillion."[176] In a more recent assessment, the top end of the estimate is even higher: "The total capital investments [CAPEX] required to build new renewable fuel plants over the whole transition period [2025–2050] are estimated at USD 4.2 trillion in the high SAF yield case, and at USD 8.1 trillion in the low SAF yield case."[177] IATA points to "eye-watering" investment requirements, rising to three-quarters of a trillion (US) dollars *per year*, globally, in 2050[178] (and not stopping in that year, but continuing to increase). The previous numbers are for capital expenditures, so-called CAPEX. In addition, there may be additional operating expenses (OPEX) such as the purchase of offsets, etc. Total costs of about $10 trillion USD globally (nearly $14 trillion CDN) fall within the range of possibility. (IATA notes that the estimated transition costs it calculates are "most likely to be at the lower end of any future possible range"[179] and that "our baseline case assumes rather optimistically that SAF product yields regarding all four major pathways are at the high end of their theoretical maximum levels."[180])

Most of those trillions of dollars will need to be turned into concrete and steel. IATA estimates the need for an additional 3,400 to 6,700 new SAF production plants between now and 2050.[181] There are less than 10,000 days between now and the end of 2050, implying the need to complete, on average, one major SAF production plant every two or three days and keep up this pace for 25 years.[182]

The SAF megaproject—the massive 500- to 1,000-fold scaleup—would be excruciatingly challenging if it was happening alone. But, as detailed previously, airlines and SAF makers will attempt this forbidding scale-up alongside numerous other industries that are planning similar scale-ups. Competition from other sectors and high costs for components and finished products, driven by ongoing shortages and exponentially increasing demands, will add to the challenge. The multiple and competing scale-up challenges should make us question the feasibility of the SAF megaproject. A consistent pattern of past failures (see next chapter) should add to our scepticism.

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176 International Air Transport Association, "Finance: Net Zero Roadmap."
177 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 1.
178 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 1.
179 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 8.
180 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 19.
181 International Air Transport Association, "Finance: Net Zero CO2 Emissions Roadmap," 1.
182 A more "realistic" scenario—the one IATA uses—is an exponential ramp-up of plant completion, rising from a handful of plants per year in 2025 to 500 per year in 2050: 1.4 production plants completed per day or one every 17 hours.

19. Past Failures to Scale Up

> "A new report ... which assessed every public climate target which the international aviation industry set itself since 2000, has shown that all but one of over 50 separate climate targets has either been missed, abandoned, or simply forgotten about. ... The industry's targets for increasing use of alternative fuels were missed every single time...."
> —Possible, 2022.[183]
>
> "Targets for Sustainable Aviation Fuel (SAF) began to appear in 2007 and at first were extremely bullish about the potential for biofuels to be deployed at scale in the run up to 2020. Over time these targets have been replaced with progressively less ambitious ones, while the original targets were quietly abandoned, as alternative fuel supplies remained multiple orders of magnitude lower than required by these original targets."
> —Green Gumption and Possible, "Missed Targets...," 2022.[184]
>
> "Target setting appears to function principally as a tactic for giving an impression of progress and action to address aviation's environmental impacts to the public and policymakers, in order to prevent any policy barriers to ongoing growth in the industry."
> — Green Gumption and Possible, "Missed Targets...," 2022.[185]

The aviation industry has recently set ambitious targets for 2030 and 2050. But these are not their first. Airlines and their industry associations have a two-decade history of setting and *missing* targets. In 2007, IATA announced a goal of 10 percent SAF use by 2017.[186] That 10 percent target has yet to be met; indeed, current blend rates are just 0.2 percent[187]—one-fiftieth of its target for 2017.

Not cowed by its failure to meet the target set in 2007, IATA tried again in 2011, though it set a less-ambitious target: 6 percent SAF (rather than 10 percent) by 2020. It failed to come close. Additional targets followed in 2012, 2014, and 2018, each less ambitious than the one before, but each time actual performance fell far short.[188] Again, SAF utilization today remains just 0.2 percent.

Given its record of missing even modest targets and given the *massive* challenge of scaling up SAF production 1,000x, we should assume that the world's airlines will fall short of their 2050 commitments. But even if airlines only miss their targets by, say, half, the negative impacts outlined above will still be large. As we get close to 2050, we may find ourselves in the worst of all possible worlds:

- even more over-dependant upon air travel as the industry achieves its doubling or tripling of travel volumes and we fail to invest in alternatives such as trains;
- contending with high emissions from air travel as SAF production is perhaps half of what is needed (and fossil fuels make up the bulk of aviation energy supplies); and
- yet still contending with significant land use, agricultural emission, food price, and sustainability impacts as a result of the production of hundreds-of-billions of litres of SAFs from feedstocks drawn from the global land-base.

In many scenarios, the 2050 SAF megaproject can cause the negative impacts outlined in previous chapters <u>and</u> fail to make air travel compatible with the need to reach net-zero globally by 2050.

183 "Aviation Industry Has Missed All but One of 50 Climate Targets in the 21st Century," Possible, May 10, 2022, https://www.wearepossible.org/press-releases/aviation-industry-has-missed-all-but-one-of-50-climate-targets-in-the-21st-century.
184 Jamie Beevor and Keith Alexander, "Missed Targets: A Brief History of Aviation Climate Targets of the Early 21st Century" (Green Gumption and Possible, May 2022), 46.
185 Beevor and Alexander, "Missed Targets: A Brief History of Aviation Climate Targets of the Early 21st Century," 5.
186 Thomhave, Ocampo, and Collins, "Greenwashing the Skies," 5.
187 International Air Transport Association, "Net Zero 2050: Sustainable Aviation Fuels," 2.
188 Thomhave, Ocampo, and Collins, "Greenwashing the Skies," 15.

20. Superior Alternatives and More-Appropriate Responses

If not the SAF megaproject, what are the alternatives? Briefly, they include:

1. Reduce demand. If we fly less, many SAF options (see next point) become more feasible.
2. Skip Bio-SAFs and go directly to Electro-SAFs. Further, require all private jets to use Electro-SAFs.
3. For travel within continents, invest in fast, energy-efficient passenger rail systems.

1. Reduce demand

Part of what makes the SAF project so damaging and unlikely to succeed is its colossal scale. Key to making the SAF project possible and positive is to make its scale workable. One way is to reduce demand—get people to fly less. Perhaps introduce a frequent-flyer levy on tickets for those who fly more than twice per year.[189] If we can reduce demand by half over the next couple of decades (to go from about 9 trillion passenger-kilometres per year today to about 4.5 trillion), many SAF options become much less damaging and less likely to fail. For those worried that such reduced air-travel volumes represent a step back to the dark ages—to a few DC-3-like creaky prop-planes plying the airways—it is revealing to learn that the last year in which flying volumes were 4.5 trillion passenger-kilometres per year was *2009*. Reverting to 2009-levels of global air travel makes many SAF options possible and potentially beneficial (see point 2). And holding air travel volumes relatively steady at those rates could mean 2050 volumes at 4.5 trillion passenger-kilometres per year rather than the currently projected 22 trillion. SAF-powered air travel could be prioritized for trans-oceanic and very-long-distance flights and trains could be used for medium-length journeys inside of continents (see point 3).

Taking steps to reduce air travel also buys time—helping defuse the near-impossible scale-up challenges outlined above. And reducing demand—reducing the number of planes in the air—also reduces non-combustion warming effects such as condensation-trail cirrus clouds. Finally, reducing demand can happen *now*, with actual emissions reductions next year, whereas SAFs slow start combined with aviation's planned rapid expansion means that emissions will remain high for years to come.

2. Go directly to Electro-SAF

Most of the negative impacts outlined in previous chapters are a result of choosing land-based fuels: Bio-SAF {seeds}, Bio-SAF {residues}, and Bio-SAF {energy crops}. The solution is to leapfrog land-sourced biofuels and move directly and rapidly to real zero-emission, zero-land-use Electro-SAFs. While this option may be impossible if air travel volumes are allowed to double, it becomes more feasible as volumes gradually trend down to half.

As an important short-term tool in creating demand and early markets for Electro-SAFs, governments should require all private jets to use such fuels within the next three or four years. The high-income individuals who use such planes are cost insensitive. Thus, private jets and their owners can serve as lucrative early markets for such fuels, enabling makers to ramp up production confident in the existence of buyers. (Globally, private jets consume about 2.5 percent of aviation fuel—about 9.5 billion litres per year[190]—making this a multi-billion-dollar market for nascent Electro-SAF makers.)

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189 As (unsubsidized) SAFs make flying more expensive, this may exacerbate exclusivity and inequality—increasingly only the rich will be able to afford to fly. Thus, governments may want to consider making a frequent-flyer levy (partly) revenue-neutral by, perhaps, providing a modest subsidy to those who travel only once per year of who have to travel for health reasons. Key is to reduce the air-miles of those who fly often while not barring infrequent flyers from accessing sometimes-crucial air travel options.

190 Thomhave, Ocampo, and Collins, "Greenwashing the Skies," 7.

3. Use trains instead

If people need to cross the ocean or go very long distances (e.g., Canada to Brazil) then Electro-SAF-powered planes are a reasonable choice. But within continents, passenger and goods transport must be moved onto trains. To accomplish this, governments must utilize their taxpayer-supplied dollars to incentivize rail rather than air travel, and governments must encourage industries to spend part of the trillions earmarked for SAFs to build railways instead—toward building extensive medium-, higher-, and high-speed rail systems throughout the Americas, Africa, Asia, and elsewhere.

This is not a report about trains, but a few points will be illuminating:

- Since 2008, China has built 37,900 kilometers (about 23,500 miles) of high-speed rail lines. The network is expected to double in length, to 70,000 kilometers, by 2035.[191]
- Between 1880 and 1918, Canada built nearly 70,000 kms of railway track—enough to cross Canada twelve times! We did so using crude tools and machines; as a young and relatively poor nation; and at a time when population densities were a fraction of those today.[192]
- One km of large-diameter oil pipeline contains enough steel to build two kms of railway track.[193]
- A passenger-rail-construction megaproject can provide jobs at family-supporting wage levels for soon-to-be displaced petroleum-sector and pipeline workers.
- Trains powered by clean renewable electricity can be true zero emission and zero warming; aircraft powered by most SAFs (esp. if blended with fossil fuels) cannot.
- Trains powered directly by electricity and driven by electric motors are much more energy-efficient than planes that require renewable electricity to be turned into liquid fuels that are combusted in jet engines. This final point is worth exploring further.

The energy efficiency of trains vs planes

Consider these two energy pathways:

Trains powered by renewable electricity
I.e., renewable electricity to trains via overhead catenary wires and on into electric motors.
Overall efficiency roughly 90 percent.

Jets powered by Electro-SAFs
I.e., Renewable electricity to direct air capture (carbon) and hydrolysis of water (hydrogen) to Fischer-Tropsch processing (to make liquid SAF) to combustion in jet engines.
Overall efficiency about 15 percent, which is the product of the next two factors:

- Electro-SAF production is about 37 percent efficient (100 kWh renewable electricity per gallon to produce, see above, while each gallon contains 37 kWh energy equivalent).[194]
- The overall (thermodynamic and propulsive) efficiency of a jet engine is about 40 percent.[195] (As in all combustion engines, much energy is lost as heat, noise, etc.)

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191 Ben Jones, "The Evolution of China's Incredible High-Speed Rail Network," CNN, May 20, 2021, https://www.cnn.com/travel/article/china-high-speed-rail-cmd/index.html.

192 Darrin Qualman, "Rail Lines, Not Pipelines: The Past, Present, and Future of Canadian Passenger Rail," *Darrin Qualman* (blog), March 6, 2018, https://www.darrinqualman.com/canadian-passenger-rail/.

193 Qualman, "Rail Lines, Not Pipelines."

194 For other estimates, see Patrick Schmidt et al., "Power-to-Liquids as Renewable Fuel Option for Aviation: A Review," *Chemie Ingenieur Technik* 90, no. 1–2 (2018): tbl. 2; Stefan Bube et al., "Kerosene Production from Power-Based Syngas – A Technical Comparison of the Fischer-Tropsch and Methanol Pathway," *Fuel* 366 (June 15, 2024): 13; Maria Fernanda Rojas-Michaga et al., "Sustainable Aviation Fuel (SAF) Production through Power-to-Liquid (PtL): A Combined Techno-Economic and Life Cycle Assessment," *Energy Conversion and Management* 292 (September 15, 2023): 1; Carlotta Panzone et al., "Power-to-Liquid Catalytic CO2 Valorization into Fuels and Chemicals: Focus on the Fischer-Tropsch Route," *Journal of CO2 Utilization* 38 (May 1, 2020): tbl. 2.

195 National Academies of Sciences, Engineering, and Medicine et al., "Aircraft Gas Turbine Engines," in *Commercial Aircraft Propulsion and Energy Systems Research Reducing Global Carbon Emissions* (Washington, D.C.: National Academy Press, 2016),

To allow for future technological advances, let us generously *double* the assumed efficiency of Electro-SAF-powered planes—grant an assumed 30 percent efficiency instead of 15. Even with this assumption, trains remain three times more efficient: 90 percent vs 30. Renewable electricity to power trains directly will provide *three times* the passenger-kilometres compared to turning that same quantity of renewable electricity into a liquid fuel and combusting it in a jet. (A 3x efficiency advantage for trains is documented in journal articles, even without the efficiency sacrifices inherent in e-fuels.[196])

At this moment in our climate crisis, is it reasonable to invest trillions of dollars into perhaps the least efficient transportation mode so-far conceived? If we can move a passenger 1,000 kms on 1 unit of electricity in a train, is it responsible public policy to instead invest in systems that require three times the energy to move the passenger the same distance? And if we do make the less-efficient choice and squander that scarce clean electricity; and potentially deny it to other, competing, decarbonization initiatives; is it honest to call Electro-SAF-powered planes a "climate solution"? As we move past 8 billion people toward 10, and as those people become more affluent and demand more travel, should we attempt to supply that travel via one of the least-efficient modes? If we do, can this be called "sustainable"?

We conclude this section with a graphic from the BBC (based on data from the UK's Department of Business, Energy, and Industrial Strategy and Department for Environment, Food, and Rural Affairs). The graphic shows climate impacts per passenger-kilometre. It reminds us that aircraft warming effects come both from fuel combustion (dark-blue bands) and other sources (light-blue). Thus, while trains may be just three times more energy efficient, they are many times more efficient when it comes to total warming effects per passenger-km because they do not create high-altitude condensation-trail clouds. Total warming effects of flights are equivalent to about 200 grams CO_2e per passenger-kilometre but the Eurostar train produces just 6—one-thirtieth as much. Even an 80 percent decarbonization of air travel (a daunting, unlikely prospect for 2050) will leave overall warming effects of planes in that distant year a large multiple of the warming effects of trains operating now. And if we clean up the electricity supply and stop burning coal and natural gas, the emissions from train shown below fall even further.

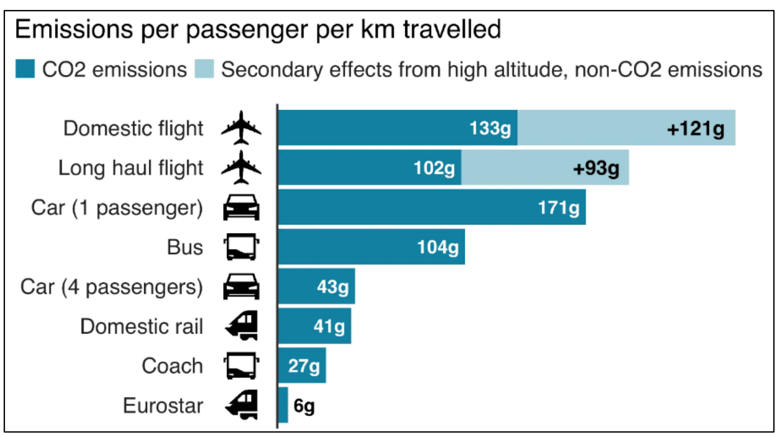

Figure 17. Emissions from various modes of travel.
Source: Reprinted from BBC.[197] BBC original cites UK BEIS/DEFRA Greenhouse Gas Conversion Factors 2019. For updated data see https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

https://doi.org/10.17226/23490; Intergovernmental Panel on Climate Change, "Aviation and the Global Atmosphere: 7.4.1.2. Propulsive and Overall Efficiency," accessed June 22, 2024, https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=97.

196 Jing-Hua Zheng et al., "A Universal Mass-Based Index Defining Energy Efficiency of Different Modes of Passenger Transport," *International Journal of Lightweight Materials and Manufacture* 4, no. 4 (December 1, 2021): 426.

197 BBC, "Climate Change: Should You Fly, Drive or Take the Train?," August 23, 2019, https://www.bbc.com/news/science-environment-49349566.

21. Conclusion

> "Large scale SAF production may actually contribute to ecological collapse rather than prevent it."
> — Thomhave, Ocampo, and Collins, "Greenwashing the Skies, 2024.[198]

Humanity is in overshoot. We are taking all the planet can sustainably give, and much, much more. That is what Steffen, Rockstrom, and others are trying to tell us when they say we have pushed past the safe operating limits for planet Earth. Already, today, we are spreading far too much fertilizer, taking too much land, and removing too much biomass. We are far past the point where any of this can be considered sustainable. Yet the SAF megaproject would require more fertilizer, land, and biomass.

The largest parts of proposed future SAF production are currently pilot projects with wholly unknown costs and chances of success. Worse, the SAF megaproject may be an energy-system and transportation dead-end that damages the biosphere. Even worse, it may be a cynical fiction designed to buy time, distract, and greenwash a high-emission sector that has plans to multiply its operations, revenues, and profits. Sustainable Aviation Fiction? Pie in the sky?

And worse still, citizens will be required to shoulder airlines' costs via tax-funded transfers to those corporations.

SAFs are not feasible decarbonization solutions, but they are very likely a food-price problem, a soil health problem, a clean energy and green hydrogen demand problem, and a cause of accelerating extinctions and warming.

Though many questions remain unanswered, we need not delay for lack of information. We know enough to act. We know enough to assess SAFs and determine whether private and taxpayer investments should be turned toward these ends, or toward alternatives.

The National Farmers Union (NFU) strongly recommends that our democratically elected leaders and our public servants:

1. **Do <u>not</u> transfer taxpayer dollars to airline and fuel companies in an attempt to facilitate a risky and damaging SAF megaproject; instead, require airlines, fuel companies, and frequent fliers to shoulder the multi-trillion-dollar costs, and in that way prevent market distortions that will have the negative effects of increasing flights and flying;**

2. **Take very seriously ecosystem limits, planetary boundaries, limits to growth, and concepts of justice when evaluating proposal such as SAFs and the plan to double or triple air travel and fuel that huge air travel load from farmland, biomass, and an already overtaxed biosphere;**

3. **Invest in *appropriate* technologies such as extensive passenger rail infrastructure; and**

4. **Act courageously, decisively, and *rapidly* to deal with climate change. Time is short to avert catastrophe. As the aviation sector might say: we're running out of runway.**

198 Thomhave, Ocampo, and Collins, "Greenwashing the Skies," 17.

Appendix 1: Acronyms

ATAG: Air Transport Action Group
AtJ: Alcohol-to-Jet
BECCS: Bioenergy with Carbon Capture and Storage
CAPEX: Capital expenditures
CI: Carbon intensity, i.e, grams of CO_2 per megajoule of energy
CO_2: Carbon dioxide
CO_2e: Carbon dioxide equivalent
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
C-SAF: The Canadian Council for Sustainable Aviation Fuel
DAC: Direct air capture
DOE: US Department of Energy
FAO: United Nations Food and Agriculture Organization
FT: Fischer-Tropsch
GHG: Greenhouse gas
GREET: Greenhouse gases, Regulated Emissions, and Energy use in Technologies, a life cycle analysis model
GWP: Global warming potential
H or H_2: Hydrogen
HEFA: Hydroprocessed esters and fatty acids
IATA: International Air Transport Association
ICAO: United Nations International Civil Aviation Organization
ILUC: Induced land use change
IPCC: Intergovernmental Panel on Climate Change
kWh: Kilowatt-hour
LCA: Life cycle assessment
LUC: Land use change
MSP: Minimum selling price
MSW: Municipal solid waste
Mt: Megatonnes or millions of tonnes
mWh: Megawatt-hour
PtL: Power to Liquids, aka Electro-SAF
RFS: Renewable Fuel Standard
RPK: Revenue passenger kilometre
SAFs: Sustainable Aviation Fuels
SOC: Soil organic carbon
tWh: Terrawatt-hour
UCO: Used cooking oil
UNDP: United National Development Programme

Appendix 2: Some Conversion factors

- Acres to hectares: multiply acres times 0.4047

- Kilometres to miles: multiply kilometres by 0.6214

- Tonnes (of jet fuel) to (US) gallons: multiply tonnes times 330
- Tonnes (of jet fuel) to (US) gallons: multiply tonnes times 1,250

Appendix 3: Calculations of land area to produce all SAF from oilseeds (canola & soybeans)

Ratios of tonnes of oilseed feedstock to litres of SAF (or renewable diesel)

Canola
688.2 litres (renewable diesel) **per tonne canola seed**. (757 million litres per 1.1 million tonnes)
"Two hundred million [US] gallons of canola renewable diesel would require about 1.1 million tonnes of canola seed, as shown in the following formula: 200 million gallons*6.5 lb/gal *0.8 lb RD/lb canola oil /0.43 lb oil/lb canola/2205 lb canola/tonne seed = 1,096,873 tonnes seed."[199]

688.5 litres (renewable diesel) **per tonne canola seed**. (568 million litres per 0.825 million tonnes)
"150 million gallons of canola renewable diesel would require about 825,000 tonnes of canola seed, as shown in the following formula: 150 million gallons*6.5 lb/gal *0.8 lb RD/lb canola oil /0.43 lb oil/lb canola/2205 lb canola/tonne seed=825,000 tonnes seed."[200]

475 litres (renewable diesel) **per tonne canola seed**.
"A canola solvent-based oil extraction plant at its optimal size of 190 million liters per year would require approximately 400,000 green tonnes of canola per year."

250-333 litres SAF per tonne of canola
"Assuming a maximised SAF yield, a small-scale plant, capable of producing 50 ML of SAF per year would require 3% of Australia's projected canola seed production in 2025 (0.2 Mt). A large-scale plant producing 300 ML per year would require 17% of canola seed production in 2025 (0.9 Mt)."[201]

262 litres SAF per tonne of canola
125,000,000 litres SAF per 477,000 tonnes of canola
100,000 tonnes SAF per 477,000 tonnes of canola
"Archer et al. [20] report it would take about 2.1 kg of rapeseed oil to produce 1 kg of SAF. Assuming 44% oil content in its feedstock, a small SAF refinery with a 100-million-kg-per-year capacity would require approximately 477 million kg of feedstock."[202]

Soybeans
186.3 litres SAF per tonne of soybeans.
18% oil by weight,[203] and oil converts to HEFA SAF at 83% by weight,[204] for a total conversion of 0.149. So, one tonne of soy makes 149 kgs of SAF.

159.7 litres of SAF per tonne of soybeans. Via 83% yield SAF from soybean oil[205]
192 litres of soybean oil per tonne of soybeans. Via division
3.35 billion litres soybean oil per 18.17 million tonnes of soybeans. Via 1079 litres soybean oil per tonne
3.24 million tonnes of soybean oil per 18.17 million tonnes of soybeans. Via 36.74 bushels per tonne

199 U.S. Canola Association, "Letter to the Honorable Michael Regan, Administrator, U.S. Environmental Protection Agency, Re: Renewable Fuel Standard Program: Canola Oil Pathways to Renewable Diesel, Jet Fuel, Naphtha, Liquified Petroleum Gas and Heating Oil," May 18, 2022, https://www.uscanola.com/wp-content/uploads/2022/05/USCA-RD-NPRM-Comments.pdf.

200 U.S. Canola Association and Tom Hance, "Fuel Pathway Requested.," March 12, 2020, https://www.agri-pulse.com/ext/resources/pdfs/EPA-HQ-OAR-2021-0845-0040_content-(1).pdf.

201 CSIRO, "Sustainable Aviation Fuel Roadmap," 2023.

202 Conner J. McCollum et al., "Estimating the Supply of Oilseed Acreage for Sustainable Aviation Fuel Production: Taking Account of Farmers' Willingness to Adopt," *Energy, Sustainability and Society* 11, no. 1 (December 2021): 33, https://doi.org/10.1186/s13705-021-00308-2.

203 Canada's Biojet Supply Chain Initiative, "HEFA Production and Feedstock Selection," 2019, 20, https://cbsci.ca/wp-content/uploads/CBSCI-HEFA-Production-and-Freedstock-Selection-single-page.pdf.

204 International Civil Aviation Organization, "SAF Rules of Thumb."

205 International Civil Aviation Organization, "SAF Rules of Thumb."

"Biodiesel consumption in 2017/2018 required production use of 3.24 million metric tons of soybean oil, or the oil from 667.44 million soybean bushels."[206]

186.46 litres of SAF per tonne of soybeans
274.10 litres of SAF per 1.47 tonnes of soybeans
72.41 gallons of SAF per 54.14 bushels of soybeans.[207]

Yield

Table 2

		Seeded area (acres)	Production (metric tonnes)	Yield (tonnes per acre)
Canola	2020	20,782,600	19,484,700	0.94
	2021	22,270,249	14,248,281	0.64
	2022	21,395,700	18,694,768	0.87
	2023	22,081,700	18,328,233	0.83
Soybeans	2020	5,070,300	6,358,500	1.25
	2021	5,157,986	6,224,029	1.21
	2022	5,274,200	6,543,158	1.24
	2023	5,630,700	6,980,525	1.24

Source: Stats. Can. Table: 32-10-0359-01

206 "Biodiesel," United Soybean Board, accessed June 4, 2024, https://www.unitedsoybean.org/issue-briefs/biodiesel/.
207 Andrew Swanson and Aaron Smith, "Alternative Land-Use Impacts of the Sustainable Aviation Fuel Grand Challenge: Corn Ethanol vs. Soybean Oil Pathways" (American Enterprise Institute, April 2024), tbl. 1.

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