Title

A Climate Club for Sustainable Aviation Fuels: Assessing Possibilities with Agent-based Modeling

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Abstract:
Previous literature has proposed that international cooperation in small groups of countries, so-called "climate clubs," will be an effective complement to the UNFCCC process. Little research has investigated the potential for an industry-specific climate club. Filling this gap, we assess possibilities for a climate club in the aviation sector in which "leader" countries pay followers to use sustainable aviation fuels (SAFs). We seek to understand if such cooperation is possible at a reasonable price. In addition, we examine the ideal coalition size for successful cooperation and the sensitivity of outcomes to SAF price and mix rate. To investigate these questions, we use an agent-based model calibrated with data on countries' populations, GDP, and jet fuel consumption. Our results indicate that modest cooperation is possible under various circumstances but limited by SAF price and maximum mix rate. Furthermore, there may be compelling reasons to start with a very small number of club members.

Introduction

Limiting the effects of climate change requires international cooperation. This is true in every sector because no one country is big enough to prevent climate change on its own and because none will be willing to take costly action if others do not also do so. The need for international cooperation is particularly acute in the aviation sector, where most emissions come from international flights. Aviation accounts for up to 3.5% of anthropogenic global warming, and this share will rise in the coming decades. Diverse stakeholders believe that sustainable aviation fuels (SAFs) will play a key role in decarbonizing aviation. In parallel, there has been scholarly interest in "climate clubs," small groups of countries that may be able to take effective climate action outside the direct purview of the UN Framework Convention on Climate Change (UNFCCC). Studies indicate these clubs can bypass hurdles in the UNFCCC process and lead to more effective climate policies.

Bridging these two areas of study, we assess possibilities for a climate club in the aviation sector in which “leader” countries pay followers to use sustainable aviation fuels (SAFs). We seek to understand if such cooperation is possible at a reasonable price. In addition, we examine the ideal coalition size for successful cooperation and the sensitivity of outcomes to SAF price and mix rate. To investigate these questions, we use an agent-based model calibrated with data on countries’ populations, GDP, and jet fuel consumption. Our results indicate that modest cooperation is possible under various circumstances but limited by SAF price and maximum mix rate. Furthermore, there may be compelling reasons to start with a very small number of club members.

In this paper, we start by reviewing the role of aviation in climate change and the international targets for decarbonizing the sector. We then discuss the measures that will play a role in reaching these goals and outline why sustainable aviation fuels (SAFs) will be at the center of these efforts. Next, we discuss the importance of effective international cooperation and why some believe that progress can be made working in small groups of countries. We review the literature on climate clubs, especially previous agent-based modelling efforts, and present our model and assumptions. Finally, we discuss our results, the implications of these results, and possible future extensions.

Aviation and Climate Change

Jet-powered aircraft burn air and fuel to create thrust, which produces carbon dioxide (CO_2), water vapor (H_2O), and smaller quantities of other emission products (FAA, 2015). Many estimates peg aviation as the source of 2-2.5% of global carbon emissions; over one billion metric tons of CO_2 per year (Lee et al., 2020). However, newer science quantifies the effects of water vapor and trace combustion products at altitude and indicates that aviation accounts for 3.5% of human-caused warming (Ritchie, 2020; Lee & Forster 2020).

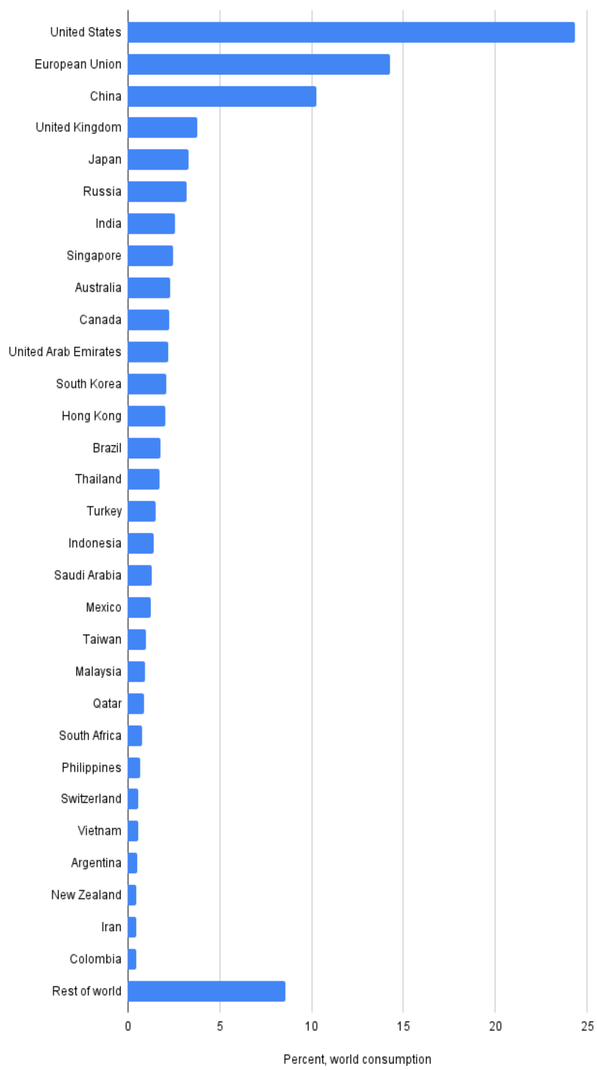
These percentages will rise as the sector is expected to grow 4.3% per year over the next 20 years (ICAO, n.d.a.). Civil aviation supports 65.5 million jobs and 3.5% of gross world product (ICAO, 2019a; n.d.a.), so managing the green transition properly is important for society and the economy. The unique institutional structure of international aviation, discussed below, makes action even more pressing. Should countries meet their Paris pledges without implementing additional measures for international aviation, the sector could rise to account for 22% of all global CO_2 emissions (Cames et al., 2015).

Jet fuel consumption by country indicates how global aviation emissions are distributed[1]. Consumption is highly skewed to the biggest users (see Figure 1; EIA, 2018). The top consumer of jet fuel (the United States) alone accounts for 24.4% of world consumption. The top 5 consumers – the US, EU, China, UK, and Japan – account for 56%. The top 30 together make up 89.2% of world jet fuel consumption.

1 While not all aircraft are jet-powered, most emissions come from jet aircraft.

Figure 1: Jet Fuel Consumption by Country

Data: EIA, 2018



Targets and Institutions

To analyze whether a SAF climate club can help reach climate goals in aviation we must understand the internationally agreed climate goals for this sector and the actors with a stake in reaching those goals (see Table I). Signatories to the Paris Agreement (2015) agreed to limit global warming to between 1.5-2°C above pre-industrial levels and reach net-zero emissions in the second half of this century. With the world already past 1°C of warming (NASA, 2020) and current policies on a trajectory for 2.0-3.6°C (Climate Action Tracker, 2021), the Paris goals are a formidable challenge.

State parties to the Agreement determine their own climate policies and communicate them in a nonbinding Nationally Determined Contribution

(NDC) updated and strengthened every five years. NDC's include plans for domestic aviation. However, international aviation, which accounts for most aviation emissions[2], is a special category ignored in nearly all NDC's[3] (Moosmann et al., 2019). This special categorization provides challenges for mitigation of aviation emissions; without policies crediting countries for reducing international transport emissions, states will not be motivated to pursue costly policies.

Plans for decarbonizing international aviation are coordinated by the International Civil Aviation Organization (ICAO), a United Nations specialized agency. Analogous to Paris NDCs, ICAO members determine and adopt individual nonbinding State Action Plans for international aviation emissions, updated every three years. At the ICAO Assembly's 40th session in 2019, member states confirmed two aspirational goals: 2% annual fuel efficiency improvement through 2050 and carbon-neutral growth from 2019[4] (Res. A40-18).

The International Air Transport Association (IATA) is a trade association representing 290 airlines that account for 82% of world air traffic, and coordinates targets and standards. IATA pledged to improve CO_2 efficiency 1.5% per year between 2009-2020 and support ICAO's plan for carbon-neutral growth beyond 2019/2020 (IATA, n.d.c). It also pledged to reduce carbon emissions 50% by 2050 from a baseline year of 2005. These industry targets encompass both domestic and international aviation (Schneider, 2021).

Table I: Key mitigation targets

Institution	Constituency	Relevant areas	Target(s)
UNFCCC; Paris Agreement	Countries, international community	National policies incl. domestic aviation	• Limiting global warming to between 1.5-2°C above pre-industrial levels • Net zero emissions in the second half of this century

2 In 2019, International aviation accounted for 30.785 billion/56.199 billion (54.8%) of aircraft kilometers flown, 12.779 million/38.299 million (33.4%) of total departures, ~1.85 billion/~4.49 billion (41.2%) passengers flown, ~5.48 trillion/~8.69 trillion (63.1%) passenger-kilometers flown, and ~194.4 billion /~225 billion (86.4%) of freight ton-kilometers flown (ICAO 2019b). Because international aviation accounts for the majority of aircraft-kilometers, and because planes flying international routes likely tend to be bigger, it is reasonable to assume that international aviation accounts for an absolute, though not overwhelming, majority of total aviation emissions.

3 The UK's updated NDC is the only one in the world taking international transport into account (Surgenor 2021).

4 Originally 2020, later adjusted due to COVID-19 (ICAO 2020).

<table>
<tr><td>ICAO</td><td>Countries, international community</td><td>International aviation</td><td rowspan="2">● Improve CO_2 efficiency 1.5% per year between 2009-2020
● A 2% annual fuel efficiency improvement through 2050
● Carbon-neutral growth from 2019/20</td></tr>
<tr><td>IATA</td><td>Aviation industry</td><td>International aviation, domestic aviation</td></tr>
</table>

Policies

Decarbonizing aviation is a formidable challenge and reaching the international goals will take multiple policies. Unlike cars, planes cannot easily run on battery power, at least not for long-haul flights, and not anytime soon (World Economic Forum 2020). Hydrogen-powered turbines or fuel cells are a future possibility, but that would require a complete overhaul of the world’s aircraft fleet and massive amounts of new infrastructure. Most stakeholders agree that achieving aviation decarbonization targets will involve a basket of policies centered around alternative fuels and offsets, with smaller contributions from operational and technology improvements.

Sustainable Aviation Fuels (SAFs)

A sustainable aviation fuel (SAF) is anything that can substitute for, or be mixed with, standard petroleum aviation fuel if it leads to emissions reductions and meets sustainability criteria (see Table II). SAFs are “drop-in” fuels, meaning they can be used in unmodified combustion engines and their associated infrastructure. ICAO, IATA, the *Clean Skies for Tomorrow* initiative, and others all place SAFs at the heart of their decarbonization strategies (Chiaramonti, 2019; Holladay et al., 2020; O’Malley et al., 2021).

Today, all approved SAFs are biofuels. Biological feedstocks such as algae, municipal waste, vegetable oil, or sugarcane pull carbon from the air into their biomass as they grow. The feedstocks are converted through any number of processes to fuel that behaves exactly like petroleum fuel. When burned, biofuels release carbon, but since this carbon was pulled from the air as the feedstock was grown the process can approach carbon neutrality over its lifecycle. In practice, energy is needed to grow feedstocks, transport, and process the fuel, so overall emissions reductions may average approximately 80% (Air Transport Action Group, 2017). Approved processes include HEFA (hydrogenated esters and fatty acids), alcohol-to-jet, and Fischer-Tropsch, each with its own feedstock and production methods.

Biofuels have been the subject of much well-founded criticism for causing biodiversity loss and raising food prices, so ICAO requires approved SAFs to meet sustainability criteria. However, these standards have still been criticized as falling short (Timperley, 2019). Many critiques of biofuels center on the massive land area needed to grow enough fuel to power the world's cars. But unlike road transport, the aviation sector has few alternatives, so it may be able to claim a large share of the biofuels that can be grown without major disruption to habitats (Victor et al., 2019).

Although it has not been commercialized, power-to-liquid represents a non-biofuel SAF. It would use energy from low-carbon sources and CO_2 to create a synthetic fuel with up to 99% lifecycle emissions reductions over petroleum (World Economic Forum, 2020). While today prohibitively expensive, power-to-liquid could rapidly become the most cost-efficient SAF as renewable energy prices drop (Roland Berger, 2020).

Unlike technology and operational improvements, SAFs can lead to major emissions reductions. Unlike battery-electric or hydrogen power planes, the technology is ready today and suitable for all flights without costly changes to aircraft or infrastructure (Air Transport Action Group, 2017). Furthermore, extensive deployment would avoid the perils of carbon offsets and obviate the need to limit flying. SAFs can be blended with standard jet fuel, increasing flexibility. At this time, there are seven approved SAF pathways, each approved up to a maximum mix rate of 50%. However, experiments have shown that this can be pushed up in the future, perhaps even to 100% (Victor et al., 2019; Huq et al., 2021).

Since their first use in a commercial flight in 2008, SAFs have been used by 45+ airlines and in over 300,000 flights (IATA, n.d.b.). While 100 million liters of SAFs are to be produced in 2021, alternative fuels still account for only 0.05% of global jet fuel demand (O'Malley et al., 2021), and expanding much further will require targeted government support (Victor et al., 2019; O'Malley et al., 2021). The key barrier to widespread adoption is cost. Depending on the pathway and government support, SAFs are at least 50% more expensive than petroleum jet fuel, and perhaps as much as six times more expensive (Victor et al., 2019). However, the relative price will narrow as petroleum prices rise (IEA, 2019).

Scaling up production is also an obstacle: replacing all conventional jet fuel with SAFs would require the construction of 170 new biorefineries per year from 2020-2050 (Chiaramonti, 2019). Large-scale use of biofuels in aviation would require refocusing the subsidies away from ground transport, which may lead to political difficulties. Despite the challenges, the unique upsides of SAF and the buy-in of so many key players all but guarantee that alternative fuels will be central to decarbonizing aviation.

Table II: What are sustainable aviation fuels (SAFs)?
• any fuel that can substitute for, or be mixed with, standard petroleum aviation fuel, if it leads to emissions reductions • SAFs in current use are all biofuels, but power-to-liquid may be viable in the future

Carbon markets

ICAO's flagship climate change program is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The program was approved in 2016 and will proceed in several incremental steps, first as a voluntary program and then in a mandatory second phase beginning in 2027. CORSIA is a market mechanism designed to make post-2020 growth carbon-neutral. Airlines are allocated carbon budgets and must either stay below or buy offset credits (Timperley, 2019). CORSIA-approved SAFs are likely to be the main way airlines will limit their emissions, and the two strategies support each other, at least in theory (Chao et al., 2019).

Beyond CORSIA, aviation was integrated in the European Union's emission trading scheme in 2012 (van Velzen, 2018). Airlines operating in Europe are required to monitor, report, and verify their emissions and pay for them with tradeable allowances (European Commission, n.d.).

Relevant to carbon markets is the concept of the social cost of carbon (SCC). This estimates the total global damage from emitting one ton of CO_2. There is much disagreement and uncertainty over the true social cost of carbon, and over the validity concept itself (Stern & Stiglitz, 2021). The Biden Administration uses US$51/ton based on an update of Obama-era studies (Chemnick 2021). Estimates from a recent meta-analysis ranged between US$-13.36 and US$2386.91 per ton of CO_2 with an average of US$54.70 (Wang et al., 2019).

Other measures

ICAO projects that SAFs and CORSIA will do most of the work in reaching midcentury goals (ICAO n.d.b.). However, other measures will also contribute. ICAO, member states, and IATA all see roles for technology and operational improvements. Each generation of aircraft has been more efficient than its predecessor, and modern planes emit 80% less CO_2 per seat compared to the aircraft of the 1950's (Air Transport Action Group, n.d.). In addition to improving technology, improving how the technology is used will contribute to meeting decarbonization goals. Everything from taxing to cruising routes can be theoretically made more efficient, especially with the use of data.

Some also see a role for limiting the demand for aviation (Exponential Roadmap, 2020; International Transport Forum, 2021b). Activists in several countries are flying less, inspired perhaps by Greta Thunberg and the We Stay on the Ground campaign (Irfan, 2019). The COVID-19 pandemic likely boosted this approach, as millions replaced business travel with teleconferencing (Global Business Travel Association, 2021). In 2021, French MPs voted to suspend domestic air routes that can be traveled by train in under 2.5 hours in an effort to limit aviation emissions (Willsher, 2021).

There are many promising strategies, centered on SAFs, that together can reach international goals for aviation decarbonization. But in both international and domestic aviation, it is the policies of national governments that will determine success or failure. Therefore, we must understand the preferences and behaviors of states in order to evaluate the possibilities for successful cooperation.

Leaders and Followers

A central theme in the institutionalist study of climate cooperation is the distinction between leaders and followers (Young, 1991; Underdal, 1994; Parker et al 2015). All countries are assumed to be rational and self-interested. At least some are leaders. They are interested in taking strong climate action and willing to spend resources to do so. They may believe it is in their self-interest, or they may have moral motivations (Sælen, 2016). However, most countries, potential followers, do not fall into this category. Followers will act only if doing so is in their narrow self-interest. This is a problem because the cohort of leaders is not big enough to bend down the trajectory of emissions on its own.

Following these assumptions, the key to global climate action is therefore for leaders to use their power and resources to induce followers to take action (Nordhaus, 2015; Victor, 2019). These inducements might be positive, like side payments or technology transfer, or negative like trade sanctions or even threats of war. If these carrots and sticks change followers' cost-benefit calculations, follower countries may find it worthwhile take climate action to gain rewards or avoid penalties, even if they care only about their own narrow self-interest. Institutionalists predict that without such inducements, followers will not take climate action and therefore climate cooperation will fail (Barret & Stavins, 2003).

Climate Clubs

Next, another problem presents itself: universal climate agreements within the UN Framework Convention on Climate Change (UNFCCC; 1992) have no structures to provide such incentives. The UNFCCC process is for coordinating actions by member states, but alone has failed to bend down global emissions (Sweet, 2016). The Paris Agreement, a major and positive step in international climate diplomacy, is based on voluntary, nonbinding action, and most countries strongly oppose incorporating substantial incentives or consequences for not meeting goals. Without these tools there is an overwhelming temptation to free ride or take advantage of the costly mitigation policies of other countries without taking comparable steps (Nordhaus, 2015; 2020).

There are other criticisms of the UNFCCC process, as well: many have noted that large, universal negotiations are complex, inefficient, and prone to gridlock (Naím, 2009; Victor 2011, 2015). Some also believe that consensus-driven multilateralism places powerful countries at a comparative disadvantage (Kahler 1992), reducing their buy-in and leading to failure (Eckersley, 2012; Breton, 2013; Falkner, 2015). Additionally, analysts have long noted that in many international accords there is an apparent tradeoff between depth and breadth; agreements are often “broad but shallow” or “narrow but deep” but rarely “broad and deep” (Barrett, 2002; Gilligan, 2004). Finally, there is a well-known tradition in political science warning of the dangers implicit in organizing large groups and the benefits of step-by-step, local organization. (Olson 1965; Axelrod 1984; Ostrom 1990). For all these reasons, much scholarly attention has been focused on making progress on climate within groups of countries outside the UNFCCC, so-called “climate clubs.”[5]

Very simply, a climate club is a group of countries coming together to solve a climate problem outside of the UNFCCC. The group must start with a small number of leaders (see Table III). Such a club might cover all climate cooperation or focus on one specific area. By working in groups outside

5 See Kahler (1992) for a critique of many of these arguments against multilateralism.

UNFCCC, leaders can provide incentives to compel others to take climate action and therefore limit free riding.

Even though it is outside, this style of cooperation could complement the UNFCCC process rather than challenge it. Detailed studies of current initiatives have found that they can be designed to be in line with UNFCCC principles, and the Paris Agreement specifically calls for action beyond the UNFCCC process (Widerberg and Stenson, 2013; Gampfer, 2016). *).* Interest in climate clubs often intersects with the scholarly interest in climate action by businesses and subnational government units, where it is taken as a given that climate progress can be made outside the meeting halls of New York and Geneva (Hale, 2016; Bernstein and Hoffman, 2018).

Across all proposals, climate clubs start with few members. By doing so, members can make progress and avoid the gridlock of large negotiations. However, many proposals see climate clubs eventually growing in membership, after the gains of starting small have been reaped. The most well-known climate club proposal, by Nordhaus (2015; 2020), entails members of a club coordinating emissions reductions and setting up trade barriers on nonmembers, thereby inducing them to join. By my definition, climate clubs exist in reality today. However, other researchers disagree, preferring narrower definitions focused on groups held together by incentives or club goods (Nordhaus, 2015; Hovi et al., 2016).

Table III: What are climate clubs?
• a group of countries coming together to solve a climate problem outside the UNFCCC • a climate club will start with a small number of countries

Modeling Climate Clubs

With the theoretical basis for climate clubs established, some scholars moved along to evaluating specific theoretical clubs. What types of rules and incentives might a climate club employ? Could a club operating under those rules be effective at curtailing emissions? Could it stay together and grow to universal membership? These research questions are well-suited to modeling, and many use agent-based modeling (ABM).

ABM is a powerful tool in which a system populated by a number of autonomous agents is created (Bonabeau, 2002). Each agent interacts with other agents and the environment according to rules specified by the modeler. Over time and with many agents, the system often exhibits surprising (“emergent”) patterns that are not intuitively deducible from the individual actors’ rules.

This study of possibilities for a SAF climate club is well suited to ABM for several reasons. First, the large number of countries makes this style of cooperation a complex and dynamic phenomenon that cannot be addressed through thought alone (Sælen, 2016). Second, there is uncertainty about the true values of several relevant variables, and ABM will allow us to easily see how different values affect outcomes. Third, actors (states) are highly heterogeneous in their motivations and capabilities, and ABM is well suited to these conditions (Wilensky & Rand, 2015).

Hovi, Sprinz, Sælen, and Underdal have pioneered the use of ABM to study climate clubs (Hovi, Ward, et al., 2015; Hovi et al., 2016; 2019; Sprinz et al., 2018). Hovi, Ward et al. (2015) and Hovi et al. (2016) reviewed extant formal models of climate cooperation and identified key elements and research questions for modeling climate clubs. Sælen (2016) studied the effectiveness of side payments for building climate clubs, finding that effective cooperation is possible with one or two leaders and side payments in the range of tens to hundreds of billions of US dollars/year. However, this is only true with a sufficiently high benefit-to-cost ratio and when actors are heterogeneous in their GDP, emissions, and vulnerability. Sprinz et al. (2018) studied the effects of the US acting as a leader, follower, or outsider on a club’s effectiveness, finding that less engagement from the world’s biggest economy lowered the scope of effective cooperation but did not rule it out. They also compared three instruments for building climate clubs: club goods, conditional commitments, side payments, and a combination of club goods and conditional commitments (Hovi et al., 2019). Although all showed potential, side payments were shown to yield the most cooperation. However, side payment schemes are not without criticism. They may be more politically difficult than other positive incentives, especially if transfers go from poorer to richer countries. Furthermore, they require oversight to ensure recipients comply with their obligations (Barret & Stavins, 2003). Finus (2003) underlines potential compliance problems with side payment systems but notes their potential when recipients are developing countries.

Modeling climate clubs builds on classic club theory as well as game-theoretic models of international environmental agreements (IEAs). Many studies of IEAs focus on side payments as a way to induce cooperation, and generally show that they can be effective (Carraro & Siniscalco 1993; Barret

& Stavins, 2003). Chander and Tulkens (1995) develop a side-payment system in which all countries contribute to side payments proportional to their private benefits from emissions reduction and receive side payments covering their costs of implementing the socially optimal level of emission abatement. They found this could maintain universal participation and universal benefit as long as countries are heterogenous.

International Climate Finance

Such side payments would be considered international climate finance, a subset of the larger category of official development assistance (ODA; non-military, non-commercial foreign aid). Donor countries agreed in 2009 to mobilize US$100 billion/year in climate finance by 2020 (Timperley, 2018). Real flows may be slightly lower (79.6 billion in 2019; OECD 2021a) or significantly lower, depending on what is counted (Buchner et al., 2019). At current levels, about 2/3rds is spent on mitigation. However, at COP26 in 2021, countries agreed that 50% of climate finance should be eventually earmarked for adaptation (Glasgow Climate Pact, 2021). The major donors of the Development Assistance Committee of the Organisation for Economic Co-operation and Development (OECD) mobilized US$161.2 billion of ODA in 2020, which amounts to 0.32% of their combined GNI (OECD, 2021b).

Model Overview

To this point, we have discussed the effect of aviation on the climate; targets, institutions, and policies for decarbonizing aviation; introduced the idea of climate clubs; and narrowed to focus on previous modeling of these clubs. Now we present our model.

We built an agent-based model that will help us evaluate conditions under which side payments from leaders can induce widespread use of SAFs in aviation and lead to emissions reductions. The coding implementation was done by Wade Schuette using *Netlogo* software. We consider a theoretical climate club whose members are UNFCCC state parties and the EU. The model is calibrated with country-level data for population, GDP, and jet fuel consumption (see Table V, Technical Appendix). The goal of the club is to mitigate aviation emissions. All members commit to using the same mix of SAF (“club-mix”) in jet fuel for all jet flights. For example, at a club mix rate of 10%, all members will replace 10% of their jet fuel consumption with SAFs. Members are designated by the modeler as either leaders or followers, depending on which set of assumptions best captures their behavior. There are no probabilistic elements in our model design. At the beginning of each model run, input values are established and leaders begin as members. Then an iterative negotiation process begins in which leaders negotiate with followers, beginning with those willing to pay for the greatest share of using SAF. A run ends when no more followers can be added and no member wants to leave.

Research Questions

With these parameters established, we investigated several questions.

Is effective cooperation possible? If so, how much would it cost?

Answering this central question requires building a working definition of effectiveness. Hovi, Skodvin, et al. (2013) define a climate agreement as effective if it (a) directly and substantially reduces emissions or (b) paves the way for a future agreement that does so. What constitutes a substantial direct reduction is open to interpretation, though meeting international targets is a reasonable starting point. If (a) does not come to pass, it is also open to interpretation what conditions fulfill (b), paving the way for future success.

There are compelling reasons that a low standard for effectiveness can be justified in this context. That is because directly meeting international aviation decarbonization goals does not absolutely require SAFs; offsets can theoretically do most of the work and any additional help from SAFs only makes it that much easier. Paving the way indirectly to meeting international goals later is an even lower bar. Even limited cooperation could create the initial demand and certainty needed to kickstart production and lower costs. Wide membership could also build norms that strengthen over time, even if each member takes only limited action at first (Finnemore & Sikkink, 1998). On the other hand, higher standards for effectiveness can be justified. Taking current international goals as a floor and seeking to limit the use of offsets might require SAFs to cut jet emissions by 50% or beyond. As a middle ground, we consider emissions reductions of 20% or more a reasonable benchmark for effectiveness given certain constraints such as limiting mix rate to 50%. When mix rate can be higher, we use a proportionally higher bar for successful cooperation, up to 40%.

Cooperation must not only be effective, it must be politically possible. This involves issues of time and political capital not modeled, but most importantly comes down to money: effective cooperation must come at (a) a reasonable total cost and (b) at a positive benefit-to-cost ratio.

What variables are most important in making cooperation possible or likely? Are there certain tipping points?
If a certain price of SAFs makes cooperation possible or likely, this information is useful both for researchers and policymakers.

What is the ideal coalition size?
Much of the academic literature on club theory focuses on coalition size (Buchanan, 1965). Indeed, the central idea behind the climate club literature is that organizing in smaller groups increases effectiveness. We are interested in determining the size of the optimal SAF club.

Leaders
In our model, leaders are exogenously motivated to pay for emissions reductions, though this generosity is limited by a hard cap that we estimate based on GDP, current international climate finance, and the share of global emissions stemming from aviation. Leaders pay for their own use of SAFs at the club mix rate.

Leaders will provide side payments to followers representing 100% of the follower's cost of using SAFs at the club mix rate, minus the follower's individual benefit from mitigation (see below). In model runs with multiple leaders, each leader's side payment burden is proportional to GDP.

Leaders will stay in the club if there is a positive global benefit. In other words, if the emissions abatement times the social cost of carbon is greater than total cost. If this condition is not met, leaders withdraw, and the model run fails.

Followers
Unlike leaders, followers are not assumed to have exogenous motivation to fight climate change, and so must be induced to act by leaders.

Followers will join the club if they receive side payments equal to the cost of using SAFs at the club mix rate minus their private benefit. For modelling purposes, a follower's individual benefit corresponds to their share of world population. For example, at a social cost of carbon of US$50, abating two metric tons of CO_2 would provide US$100 in global benefits. If the follower making those cuts accounts for 1% of world population, then they would directly accrue US$1 in individual benefits, and require side payments for the remainder of the cost of abating those two tons. We can say that the "co-pay" required from this country is 1%.

On the one hand, this compensation scheme seems overly generous on the part of leaders; in practice few may be willing to pay such a high proportion of costs. On the other hand, potential followers demanding generous recompense from leaders in return for climate action is a time-honored tradition of climate diplomacy. If fact, for some groupings, like the so-called "Like-Minded Developing Countries" negotiating block, this rule, in which followers pay for their own direct gains, may be considered too little support from leaders.

Inputs

The uncertainty of several present and future values is a key reason ABM is well-suited to this research question; the modeler can easily observe how different values affect outcomes.

Club mix

The modeler can define "club-mix" anywhere between 0-100, therefore changing the percent of total jet fuel each member will replace with SAFs.

SAF cost

The modeler can set the ratio of SAFs to petroleum jet fuel cost at any figure above 100%.

Lifecycle emissions reduction

In our investigation, we mostly held the variable constant at 80%, but the user can input any value.

Social cost of carbon (SCC)

Including this is essential to our effort because both leaders and followers are expected to make rational and self-interested decisions based on costs and benefits, which involves translating emissions into financial consequences. While our model can use any value, we generally use US$50-54/ton.

Jet fuel price

At the time of writing, the world average jet fuel price was ~US$1.70/gallon, although this varied somewhat by region (IATA, n.d.a.). This value was generally held constant, although future users of the model will be able to experiment with varying it.

Transaction costs

The model has a variable transaction cost that is subtracted for each member added that can range from trivial (US$1,000) to improbably expensive (US$10 billion). Total costs are subtracted from the leaders' maximum willingness to pay but payments are not transferred to followers. This can represent concrete startup costs for adding another country, like training and equipment. It can also represent more abstract costs like the added complexity of negotiation as membership grows. Translating the marginal difficulties of adding a member to a club into a dollar figure is inexact but a necessary abstraction for this model.

Leadership

Observing the varying outcomes from different configurations of leaders was a key interest of previous work in this area (Sprinz et al., 2019). Our model is able to have any country or group of countries act as leader. We consider five actors as potential leaders: the United States, China, the European Union, Japan, and the United Kingdom. We tested every configuration of leadership in which at least one of these five is a leader and no others are leaders: a total of 31 configurations. The basis for selecting these five is strong; they are the five biggest consumers of jet fuel and have the five largest economies. They are also the top providers of international climate finance and aspire to global political leadership.

There are strong reasons to suspect that at least one of these five would have to lead in any viable climate club. If all remained outside, the group could never cover more than 44% of global jet emissions. If none acted as leaders but one or more joined as followers, smaller and poorer countries would have to step up to provide climate finance. Beyond that, these small potential leaders would have to pay not just other small or poor countries but also countries bigger and richer than themselves. This is a political nonstarter in international climate negotiations and highly unlikely. If the small cohort of other developed countries (for example Norway, Switzerland, New Zealand, and South Korea) joined together, they may achieve results similar to those of one or two of the five potential actors we consider. However, future modelers may find it useful to expand potential leadership groups, and they can use our model to do so.

Maximum willingness to pay

As a starting point in determining the most leaders would be willing to pay, we consider current international climate finance flows for mitigation and the fraction of total warming from aviation. If aviation accounts for 3% of warming, and current financing for mitigation amounts to around US$50 billion (OECD, 2021a), then US$1.5 billion of available finance for the aviation sector is a reasonable number if all climate finance donors (UNFCCC Annex I countries) pay.

However, there are reasons the actual willingness to pay may be higher or lower. First, the list of leaders will likely not encompass all Annex I countries. Also, the total available funds may need to be split among the rest of aviation mitigation measures and not kept solely for SAFs. Conversely, the well-organized aviation industry may be well positioned to ask for financial support. The key variable is how governments view the fact that aviation is one of the hardest and most expensive sectors to decarbonize. They may prefer to spend their limited funds elsewhere, where returns in the form of emissions reductions are cheaper. Alternatively, they may acknowledge the expense of aviation mitigation and allocate to it a greater percentage of climate finance. Ambition may fall or (more likely rise), changing the total amount countries are willing to spend.

In the model, maximum willingness to pay is represented as a fraction of the total GDP of each leader. 2020 GDPs (World Bank, Table IV) for the five potential leaders are US$20.9 trillion (United States), US$15.3 trillion (European Union), US$14.7 trillion (China), US$5 trillion (Japan), and US$2.7 trillion (United Kingdom). The top three have a combined GDP of US$50.9 trillion, while all five together add up to US$58.6 trillion. A limit of 0.01% of GDP would mean that the US alone would pay US$2.09 billion, and all five together would pay US$5.86 billion. This seems generous but reasonable as an upper limit. We also model a hard limit of 0.005% of GDP, which would entail up to US$1.045 billion from the US and maximum payments of US$2.93 billion if all five countries led.

Table IV: Maximum side payments

Leader	2020 GDP, US$	0.01% GDP contribution, US$	0.005% GDP contribution, US$
United States	20.9 trillion	2.09 billion	1.045 billion
European Union	15.3 trillion	1.53 billion	765 million
China	14.7 trillion	1.47 billion	735 million
Japan	5 trillion	500 million	250 million
United Kingdom	2.7 trillion	270 million	135 million

As stated above, transaction costs are subtracted from these totals, and multiple leaders split the bill according to GDP. Limits on international climate finance come from the domestic politics of international aid; it is not generally popular to send more than a small fraction of the government budget to other countries, regardless of its use. Conversely, politicians are less likely to block funding for domestic use of SAFs, which in fact can support domestic industries. For this reason, a leader's spending on SAFs at home is not subtracted from its hard cap on side payments.

Results

We ran several experiments encompassing over one hundred thousand model runs (see Technical Appendix). We used basic statistical analysis and other methods to identify trends. Since we are assessing possibilities, it made sense to review individual pathways leading to successful emission reductions and note common features of these successful runs. Future researchers can apply more sophisticated quantitative analysis to model results, which was beyond the primary author's expertise. However, we were able to identify several interesting results applicable to the real world.

Modestly successful cooperation is possible in a range of circumstances

Modestly successful cooperation (20%+ emissions reduction) is possible under a range of circumstances. This cooperation is possible with side payments under US$5 billion and with positive benefit-to-cost ratios. Experiment A (99,840 model runs; mix rate 10%, 30%, 50%, 80%, 100%; see below for details) yielded 5,020 pathways to a 40%+ jet emissions reduction. Every single one of these successful pathways used a mix rate of 80% or 100%. They had an average benefit/cost ratio of 15.76 and a minimum benefit/cost ratio of 2.30. There was an average total cost (side payments + transaction costs) of ~US$4.78 billion. Experiment B (4,160 model runs, see below for details) limited mix rate to 50% and still showed paths to successful cooperation. It yielded a maximum emissions reduction of 38.5% and 548 pathways to a 20%+ jet emissions reduction. These pathways had an average benefit/cost ratio of 5.09 and a minimum benefit/cost ratio of 2.27. There was an average total cost of ~US$3.32 billion.

Maximum mix rate defines the ceiling on effectiveness

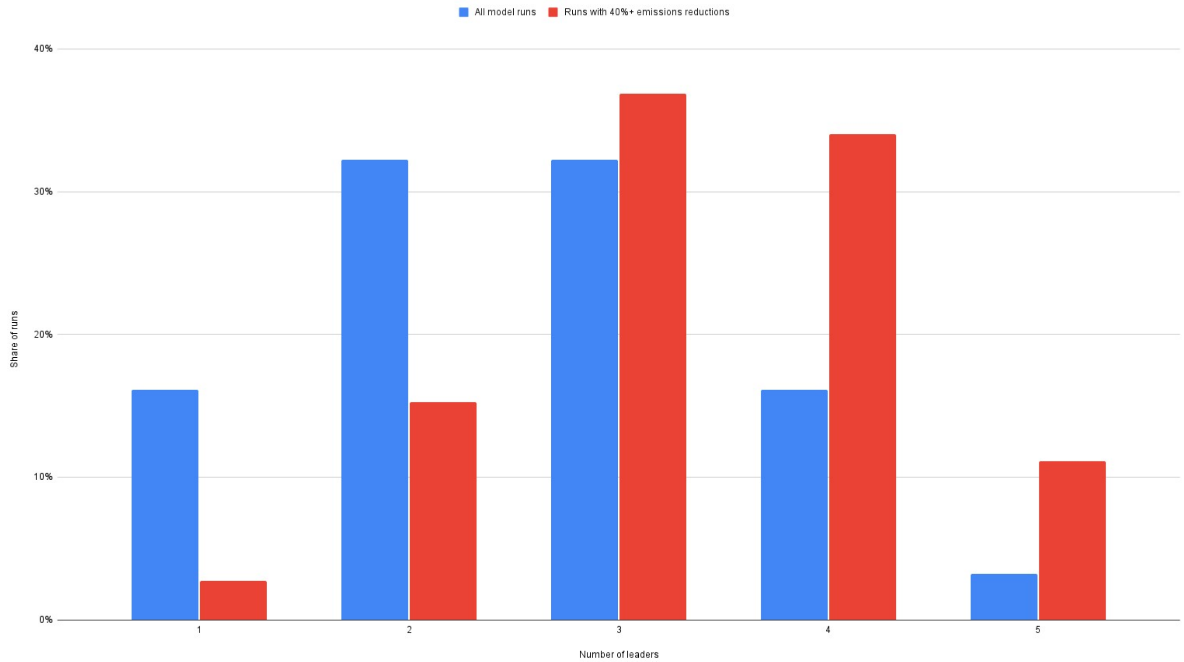
Model results indicate that the absolute ceiling on emissions abatement is defined by $a*b$ in which a is the maximum mix rate as a fraction and b is the per-unit emissions reduction of SAF as a fraction. If SAF leads to 80% per-unit emissions reduction and maximum mix rate is 50% then the total emissions abatement cannot exceed 40%. It is easy to see that this also applies in the real world. As the aircraft fleet turns over and technology advances, maximum mix rate should increase, leading to larger potential gains, and per-unit emissions reduction could increase as renewable electricity makes production of biofuels greener and power-to-liquid easier. These results indicate that in the long term, abating more than 40% of jet emissions will require these technical advances, and so resources would need to be allocated to basic and applied research. In practice, however, the price gap and the time needed to scale up production are likely to limit demand for SAFs well below 50% for some time.

No single country must lead

Cooperation is theoretically possible under several leadership configurations; there is not a single actor that must be a leader for the club to work. However, more leaders make effective cooperation more likely. The US, EU, or China may each be an effective sole leader, but Japan and the UK may not be. In Experiment A, the US was a leader in 83.1% of runs reducing emissions 40%+. The EU led in 74.1%, followed by China at 68.8%, Japan at 55.2%, and the UK at 54.1%. In 138 successful runs with only one leader, that sole leader was the US 70 times, the EU 36 times, China 32 times, and Japan and the UK zero times. Runs with 40%+ emissions reductions were disproportionately likely to have a higher number of leaders than all runs in general (see Figure 2).

Experiment B produced very similar results. In runs producing 20%+ emissions reductions, the US led 79.6%, followed by the EU at 68.4%, China at 63.5%, Japan at 55.7%, and the UK at 54.4%. Successful runs again tended to have higher than average numbers of leaders compared to all model runs. In 19 successful runs with a sole leader, the US led nine times while China and the EU each led 5. Previous studies of climate club leadership (Sprinz et al., 2018) have shown that the buy-in of major powers is helpful but not absolutely necessary to a successful club. Our results mirror this finding.

Figure 2: All model runs vs. runs with 40%+ emissions reductions (Experiment A)

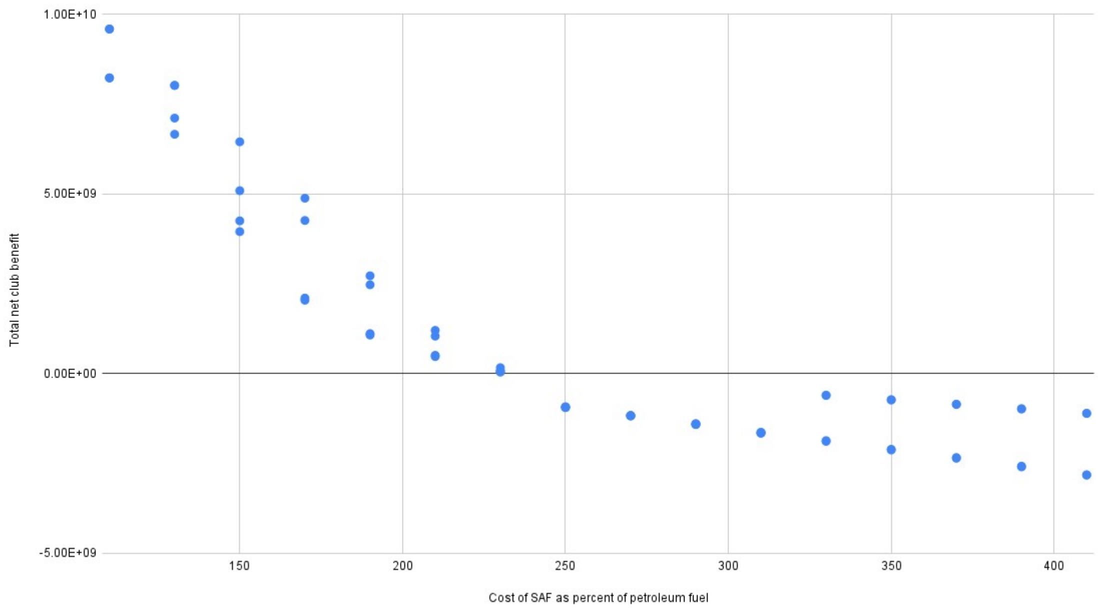


Lower SAF price supports effective cooperation

Unsurprisingly, cheaper SAF leads to more effective cooperation and a greater net global benefit (Figure 3, Experiment D). Gains rapidly diminish as SAF becomes more expensive: using SAF costing 140% the price of petroleum fuel will require four times the side payments than SAF costing 110%.

Notably, we model the price of SAF as a fraction of the price of petroleum fuel; therefore changes in standard jet fuel cost are relevant. If the price of jet fuel increases as a result of carbon price policies or other factors, SAF will become relatively cheaper. The per-unit cost of SAF is also likely to come down over time as the market share expands.

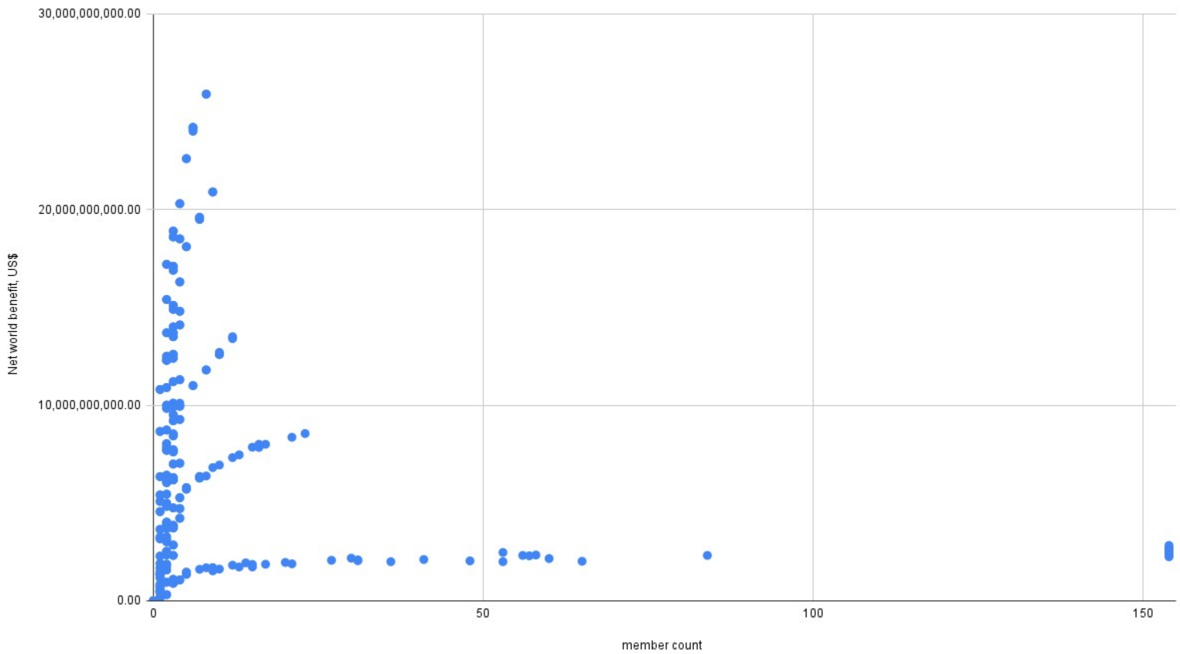
Figure 3: SAF price vs net club benefit



Universal membership is possible but not efficient

Under favorable conditions, the club may expand so that every country joins and 100% of world jet fuel emissions are covered. Several factors can contribute, including low SAF price, low mix rate, low transaction costs, high social cost of carbon, and high willingness to pay. However, more conservative figures curtail this possibility. When maximum willingness to pay is set at 0.05% GDP and SAF is at least twice as expensive as petroleum fuel, the only clubs that can reach universal membership have a low (≤10%) mix rate (Figure 4, Experiment F) and these clubs are inefficient, as we discuss below.

Figure 4, Net world benefit vs. member count



Leader-only clubs can work

At the other extreme are possibilities of clubs composed exclusively of leaders. The fact that jet fuel use is heavily concentrated (56% of global demand) among the five potential leaders means that this route can lead to effective emissions reductions, lowering global jet emissions by up to 22.4%. Leader-only clubs have the highest benefit-to-cost ratio of any modeled pathway for the simple reason that leaders' costs for domestic implementation of SAF are ignored in our model. However, this is not simply an artifact of our choices; it applies to the real world; governments spend a miniscule fraction of their budgets on foreign aid. It is beyond question that they find it far more popular to spend money at home than to send it abroad.

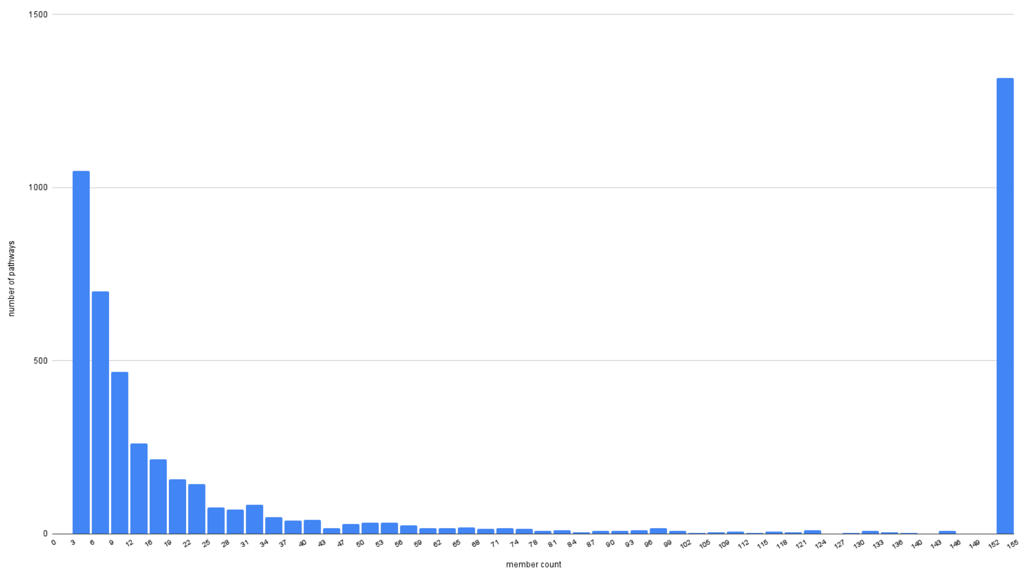
We can assume that a country's national budget is aligned with its politics. If it spends 1% of its budget on foreign aid, then politics permit $1 of international aid spending for each $99 spend at home. With this rough logic, spending $50 million at home is far more politically feasible than spending $1 million on a foreign project. This line of reasoning is far from exact, but it indicates that governments will find less opposition to domestic SAF subsidies. Politicians in potential leader countries may therefore find it much easier to cooperate with another large country to harmonize SAF use without side payments than they would to subsidize the SAF use of followers.

We can summarize this logic: rational leaders in a SAF climate club want to maximize emissions reductions, the net benefit to the world, and the benefit-to-cost ratio for themselves. If universal adoption of SAFs is not possible with what leaders are willing to pay, they will have to look for the “cheapest” barrels of petroleum to replace with SAF. This maximizes not only the benefit-to-cost ratio, but also emissions reductions and net benefit. First, leaders will search for the barrel of petroleum fuel that is cheapest for them to replace with SAF. Once it has been replaced, it is only logical to search for the next cheapest-to-replace barrel, and so on. Because implementing SAF at home does not require international side payments, it will be cheapest for leaders to start with the fuel they use themselves. This result applies to both the model and the real world. The top five consumers of jet fuel could build a club encompassing 56% of jet emissions by bargaining among themselves, all without paying followers or dealing with the complexity of a large group.

Small clubs are a compelling option

Leaders may find it worthwhile to provide some amount of funding to followers to deepen overall emissions cuts, even if this lowers the benefit-to-cost ratio of the scheme overall. Their generosity is not without limits, but they may be willing to pay something. Critically, the logic of the previous section extends past the cohort of leaders. Even when leaders need to engage with followers, it makes sense to keep the club small. A histogram of successful clubs (Experiment A, Figure 5, ignoring net benefit) shows that these groups tend to stay small if they cannot grow to universality, and that this trend extends beyond the five-member, leader-only club.

Figure 5: Histogram of model pathways leading to 40%+ emissions reductions (Experiment A)



This result is easily explained. Every country has a maximum amount of SAF it can use, depending on its total jet fuel consumption and the maximum mix rate, which is a technical factor beyond political control. In a world in which SAF is approved up to a 50% mix rate and in a country that consumes 1,000,000 barrels of jet fuel per year, the country be considered “filled” once it uses 500,000 barrels of SAF per year. Every potential follower also has a “co-pay” rate. That is, the percentage of the cost of implementing SAF that they are willing to pay themselves and therefore will not require from side payments. Just as it makes sense for leaders to start a cooperation scheme among themselves because it is cheapest, it makes sense to extend the club first to followers with the highest co-pay rates. In other words, potential followers will be allowed to enter the club in order of how much of the marginal costs they are willing to pay themselves. Furthermore, it is not efficient to extend club membership to countries willing to pay less until countries with higher co-pays are filled.

In our model, our co-pay rate is tied to population; larger countries reap a large share of gains from emissions reductions themselves, so are willing to pay more. In turn, leaders will first deal with these countries because it is most efficient to do so. Put simply, it does not make sense to move on to the next country, willing to pay a smaller share of the overall cost, until the countries willing to pay more are filled. It is always most efficient to replace the maximum amount of SAF possible in countries with the highest co-pay rates before moving on to the next country. This is true even if the co-pay rate is not determined by population and even without considering transaction costs. All in all, it makes sense for potential leaders seeking decarbonization of the aviation sector to work in a small club.

Conclusion and Extensions

We sought to add to the discussion on climate clubs by using modeling and focusing on one particular sector: aviation. We hope this work can in some way contribute to the academic debate. Building on previous studies, we made decisions on how to a model climate club. Our results indicate that successful cooperation is possible, subject to constraints. One particular country need not lead in order for the scheme to be successful. We also found that, in the short term, real progress can be made in decarbonizing aviation. If a small initial investment in SAF leads to a virtuous cycle of falling prices and stringent policies, a modest investment can successfully decarbonize the aviation sector. However, action is needed outside the direct purview of such a club. Most notably, technical progress on scaling up production of SAF and pushing up the maximum mix rate will be needed before midcentury to meet goals.

A central irony in the climate club literature is that, for many, effective clubs are not expected to remain small. Club theory identifies several benefits to small group organization, and many proposals expect clubs to start small and take advantage of these benefits in order to build a solid foundation for future growth into a large group. This may be the case in most international environmental agreements, but for a SAF club, there is compelling logic to remaining small. In addition to the literature supporting the benefits of small groups, we found that small clubs, composed of only leaders or of leaders and a limited group of followers, have distinct advantages.

Our model is available for free download online (see Technical Appendix) and future researchers may consider extensions to the model or analysis. Most notably, we ignored carbon prices, which would narrow the price difference of SAFs with respect to petroleum fuel. Current and future carbon price policies will have a major effect on the viability of scaling up SAFs and building international cooperation around it. Additionally, there are regional price differences for jet fuel that may change which countries are most willing to use an alternative. Extensions could define a more precise standard for effectiveness by integrating functions for technology substitution and price changes over time. This would shed light on how much initial demand will lower prices and hence improve prospects for future cooperation. The model would look much different if leaders offered to pay less than 100% of followers' costs, although modeling this might incur compliance issues, also worth studying. Our model assumes the only limit to SAF adoption is cost and ignores the real challenge of growing feedstocks, production, and distribution. It also does not distinguish between different SAF pathways.

Opening up the "black box" of supply and integrating such factors into a model is highly worthwhile. Similarly, moving past the unitary state assumption and delving into the decision-making processes would prove valuable, and we are interested in understanding the differences in inducing compliance between democracies and authoritarian regimes. Tackling climate change requires working sector by sector, and until now climate club modeling has not focused on mitigation in general. Researchers interested in our approach could fill this gap by modeling cooperation in other areas like shipping and blue carbon sequestration.

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Disclosure
I report no conflict of interest relevant to this work.

Technical Appendix

Table V: Data sources	
Figure	Source
UNFCCC Parties list	United Nations Framework Convention on Climate Change. 2018. Parties. https://unfccc.int/process/parties-non-party-stakeholders/parties-convention-and-observer-states

Population	United Nations Population Division. World Population Prospects: 2019 Revision. https://population.un.org/wpp/
GDP	World bank. 2021. World Bank national accounts data. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD Organisation for Economic Co-operation and Development. N.d. Gross Domestic Product (GDP). https://stats.oecd.org/index.aspx?queryid=60702
Jet Fuel Consumption	Energy Information Agency. 2018. Petroleum and Other Liquids. https://www.eia.gov/international/data/world/petroleum-and-other-liquids/annual-refined-petroleum-products-consumption?pd=5&p=0000000000g&u=2&f=A&v=mapbubble&a=-&i=none&vo=value&t=C&g=00000000000000000000000000000000000000000000001&&l=249-ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvnvvvs0008&s=315532800000&e=1577836800000 *2018 World jet fuel consumption 14.507 quad BTU = 14.507 * 10^9 million BTU*
Conversion from	*2018 World jet fuel consumption*

consumption to spending	*14.507 quad BTU = 14.507 * 10^15 BTU.* = 2,558,553,792 barrels. At a price of US$76.6/bbl, total world spending on jet fuel = US$195,985,220,467. ≈ US$196 billion. Spending by potential followers (0.44 of world) = US$86.24 billion.
Conversion from jet fuel consumption to emissions	Energy Information Agency. 2016. Carbon Dioxide Emissions Coefficients. https://www.eia.gov/environment/emissions/co2_vol_mass.php *Jet fuel emissions: 70.9 kg CO_2 / million BTU* *World jet fuel emissions: 14.507 * 10^9 * 70.9 kg CO_2 = 1.02855 * 10^12 kg CO_2 = kg CO_2 = (1.02855)*(10^9) tons CO_2* Since the primary work on this study, *EIA updated jet fuel emissions to 72.23 CO_2 / million BTU. We used the 2016 number.*
	Energy Information Agency. N.d. Energy Consumption by Mode of Transportation. https://www.bts.gov/content/energy-consumption-mode-transportation Jet fuel heat to volume: 135,000 BTU/gallon or 5,670,000 BTU/barrel.
Secondary Data Sources	Worldmeters. 2021. Eritrea, Niue population; Cuba, Iran, Syria, Turkmenistan GDP. https://www.worldometers.info Statista. 2021. South Sudan GDP. https://www.statista.com/topics/4183/south-sudan/

Download our model at: Insert link to download model here

Our R Code

Behaviorspace experiments:

Experiment A (99,840 model runs)
["Social-cost-carbon" 54 100]
["JET_FUEL_USD_PER_GALLON" 1.7]
["fund-gdp-percent-scaled" 500 1000 2000] (Maximum willingness to pay 1000= 0.01%)
["China-go" true false]
["USA-go" true false]
["EU-go" true false]
["JPN-go" true false]
["UK-go" true false]
["Cost-percent" [110 25 410]]
["transaction-cost-log" 5 6 7 8] (transaction cost = 10^x)
["saf-mix-percent" 10 30 50 80 100]
["Emissions-reduction-percent" 50 80]

Experiment B (4,160 model runs)
["Social-cost-carbon" 54]
["JET_FUEL_USD_PER_GALLON" 1.7]
["fund-gdp-percent-scaled" 1000]
["China-go" true false]
["USA-go" true false]
["EU-go" true false]
["JPN-go" true false]
["UK-go" true false]
["Cost-percent" [110 25 410]]
["transaction-cost-log" 7]
["saf-mix-percent" [5 5 50]]
["Emissions-reduction-percent" 80]

Experiment C (64 model runs)
["Social-cost-carbon" 54]
["Cost-percent" [110 20 410]]
["fund-gdp-percent-scaled" 500 1100]
["max-ticks" 250]
["transaction-cost-log" 6 7]
["JET_FUEL_USD_PER_GALLON" 1.75]
["saf-mix-percent" 50]
["Emissions-reduction-percent" 80]
["SCENARIO" 9]
["LEADER_LIST_DEPTH" 3] (US, EU, China)

Experiment D (1,664 model runs)
["Social-cost-carbon" 54]
["Cost-percent" [110 25 410]]
["fund-gdp-percent-scaled" 1000]
["China-go" true false]
["USA-go" true false]
["EU-go" true false]
["JPN-go" true false]
["UK-go" true false]
["max-ticks" 250]
["transaction-cost-log" 5 6 7 8]
["JET_FUEL_USD_PER_GALLON" 1.75]
["saf-mix-percent" 50]
["Emissions-reduction-percent" 80]

Experiment E (4160 model runs)
["Social-cost-carbon" 54]
["JET_FUEL_USD_PER_GALLON" 1.7]
["fund-gdp-percent-scaled" 500]
["China-go" true false]
["USA-go" true false]
["EU-go" true false]
["JPN-go" true false]
["UK-go" true false]
["Cost-percent" [110 25 410]]
["transaction-cost-log" 6 7]
["saf-mix-percent" 10 30 50 80 100]
["Emissions-reduction-percent" 80]

Experiment F (320 model runs)
["Social-cost-carbon" 54]
["JET_FUEL_USD_PER_GALLON" 1.7]
["fund-gdp-percent-scaled" 500]
["China-go" true false]
["USA-go" true false]
["EU-go" true false]
["JPN-go" true false]
["UK-go" true false]
["Cost-percent" 200]
["transaction-cost-log" 6 7]
["saf-mix-percent" 10 30 50 80 100]
["Emissions-reduction-percent" 80]

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