Dynamic climate clubs: On the effectiveness of incentives in global climate agreements

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A proposal to combat free riding in international climate agreements is the establishment of a climate club—a coalition of countries in a structure to encourage high levels of participation. Empirical models of climate clubs in the early stages relied on the analysis of single-period coalition formation. The earlier results suggested that there were limits to the potential strength of clubs and that it would be difficult to have deep abatement strategies in the club framework. The current study extends the single-period approach to many periods and develops an approach analyzing "supportable policies" to analyze multiperiod clubs. The major element of the present study is the interaction between club effectiveness and rapid technological change. Neither alone will produce incentive-compatible policies that can attain the ambitious objectives of international climate policy. The trade sanctions without rapid technological decarbonization will be too costly to produce deep abatement; similarly, rapid technological decarbonization by itself will not induce deep abatement because of country free riding. However, the two together can achieve international climate objectives.

climate change | integrated assessment | climate club | supportable policies | carbon prices

Global agreements on climate change date back to the Kyoto Protocol in 1997, yet little substantial coordinated abatement has taken place. Free riding is a major hurdle in curbing global externalities and is at the heart of the international failures to deal with climate change. Without an appropriate incentive structure, no individual country has an incentive to cut its emissions sharply. Moreover, if there is an international agreement, nations have a strong incentive not to participate. If they do participate, there is a further incentive to miss ambitious objectives. The outcome is a noncooperative free-riding equilibrium in which few countries undertake strong climate change policies—a situation that closely resembles the current international policy environment. Nations speak loudly but carry the tiniest of sticks.

One proposal to combat free riding is the concept of a climate club, which is a coalition of countries organized to encourage high levels of participation and abatement. The idea, analyzed in ref. 1, is that nations can overcome the syndrome of free riding in international climate agreements if they adopt the club model rather than voluntary arrangements. The central feature of the club model is that the structure includes both obligations in terms of strong abatement and penalties for either nonparticipation or failure to meet the club obligations.

The club model analyzed here centers on an "international target carbon price" that is the focal provision of the agreement. (The power of the price as a single instrument has been shown in ref. 2.) For example, countries might agree that each country will implement policies that produce a minimum domestic carbon price of $50 per metric ton of CO_2. The target price might apply to 2025 and rise over time at, say, 3% per year in real terms. Carbon prices might be determined by either a cap-and-trade system or by carbon taxes as best fits the structures of individual countries, but many details for measuring remain to be determined. Additionally, no consideration is given to transfers among regions.

The need for a special type of agreement is required by the combination of climate as a global public good and the lack of a mechanism for requiring participation of individual countries. Both the theory and history of international agreements show that some form of penalty is required to induce countries to participate in agreements with local costs but diffuse benefits (see particularly refs. 3 and 4). While the exact degree of free riding and cooperation will differ according to the technology and the assumptions about coalition formation and stability, most theoretical and empirical modeling suggests that reaching a grand bargain of most regions with strong abatement will be extraordinarily difficult (5–9). Studies of club-like structures can be found in refs. 10–14. For an independent empirical modeling analysis, see ref. 15.

The original proposal in the climate club was a uniform tariff on all imports of nonclub countries into the club. Take as an example a penalty tariff of 5%. If nonparticipant country *A* exports $100 billion into the club region, it would be penalized by $5 billion of tariffs. In calculations of the coalition stability of a one-shot climate club using the Coalition-DICE (C-DICE) model (1), it was estimated that climate clubs would be extremely effective (relative to no club) for low carbon prices (less than $100/tCO_2$ in 2015). Those estimates also showed that a club would have difficulty supporting higher carbon prices at the current economic structure.

However, that analysis was limited to a single period. The reason was that the computational complexity of the C-DICE model was too great for a full dynamic model (see *SI Appendix* for a discussion of complexity). The present study tackles the question of sustainable climate clubs in a multiperiod framework.

Significance

Global agreements on climate change date back to the Kyoto Protocol in 1997, yet little substantial coordinated abatement has taken place. Free riding is a major hurdle in the solution of global externalities and is at the heart of the international failures to deal with climate change. The present analysis presents a dynamic model of a climate club and shows that club incentives through tariff penalties and rapid decarbonizing technological change can achieve the international objectives of governments.

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Here are the major results. The major analytical concept developed here is a "supportable policy." This designates the upper bound on a contribution to the public good that is compatible with the incentives contained in the agreement. At the most general level, supportable policies are ones that will minimize carbon emissions each period subject to a constraint that the policy is incentive-compatible with the agreement. More precisely, the supportable policy is one in which the costs of participating (through abatement) just equal the costs of nonparticipation (imposed through the trade sanctions). We can interpret supportable policies as ones with maximum stringency given the incentives to be in the club (here, the incentives are tariffs, but they could be something else). The required policies could be emissions prices, emissions limits, or other constraints on producer and consumer behavior, although the present study examines supportable carbon prices. Policies that have target carbon prices lower than the supportable price have lower abatement; policies with higher target carbon prices induce countries to drop out of the club and therefore also have lower abatement. The study defines supportable targets, shows how to find them in a simple example, and then develops a global empirical model that allows the calculation of supportable policies over time.

A second contribution is to develop a simple analytical model of the supportable participation of a country in a regime (such as a climate club) that imposes costs but also conveys rewards for participation (or imposes punishments for nonparticipation). While estimating the equilibrium of a coalition in a dynamic framework is computationally extremely burdensome, as noted in *SI Appendix*, determining supportable policies is relatively simple both analytically and computationally for the multiperiod model.

A third finding in a simple analytical model provides the key determinants of supportable policies. It shows that the time path of supportable policies for the climate club depends primarily on six determinants. These are trade openness (the trade–output ratio), the tariff rate, the rate of decarbonization, the fraction of the world in the club, the welfare loss per unit tariff, and the rate of technological change in the backstop technology. Additionally, in the simple model, the growth of output does not affect the outcome because it cancels out for costs and benefits.

The fourth contribution is developing a simple global computable model (Trade DICE or TDICE) for estimating supportable carbon prices, emissions, and geophysical variables such as concentrations and temperature. The model uses much of the structure of the standard DICE model (described in *Modeling Details*) but adds equations that represent the public-goods character of damages, "club" variables such as trade, the gains from trade, and the costs of trade sanctions. By combining the different components, it is possible to determine the supportable carbon prices and emissions—that is, policies in which emissions are minimized subject to the constraint that the costs of participating just equal the costs of nonparticipation.

Fifth, the results of the TDICE model show several features. First consider a scenario with baseline technology and other parameters. Even with strong trade sanctions of 10% uniform tariffs for nonparticipation, emissions are slowed sharply in the club relative to no club policy but do not attain the high levels of abatement that are the objectives of international climate policy. With baseline parameters and strong sanctions, industrial emissions in 2050 are 26 $GtCO_2$ rather than the target of zero. The global temperature in 2100 reaches 3.1 °C rather than the 1.5 or 2 °C targets. This result confirms the conclusion in ref. 16 that the incentives in the climate club as originally conceived are insufficient to attain international objectives.

A sixth finding shows the importance of the combination of the club incentives and rapid decarbonizing technological change. Two important parameters in the analysis are the rate of decarbonization and the rate of technological change in the backstop technology. Technological improvements provide powerful boosts to the club incentive because they lower the cost of participation. As a polar and ambitious objective, the model examines the club incentives along with a rapid rate of decarbonization (2% per year faster than historical rates) as well as a rapid decline in the cost of the backstop technology (at 4% per year instead of 1% in the base assumption). With these assumptions and the strong tariff incentive of 10% penalty tariff, global emissions in the TDICE model are slightly negative in 2050, and global temperatures stay within the 2 °C limit. While the combination of a strong club and rapid technological change are at the outer edge of political and technological realism, they do point to a potential political–economic–technological mechanism for attaining ambitious climate objectives.

Finally, the major surprise of the study is the interaction between the club structure and rapidly decarbonizing technological change in a dynamic framework. Neither a club nor rapid technological change by themselves will produce incentive-compatible policies that can attain the ambitious objectives of international climate policy. The trade sanctions without rapid technological decarbonization will be too costly to induce highly costly deep abatement; similarly, rapid technological decarbonization by itself will not induce deep abatement because of country free riding. However, the two together—providing incentives to participate but lowering the costs of participation at the same time—are a team that, in principle and according to the current study, can achieve the international objectives.

Analytical Extension of Climate Clubs for Many Periods

Clubs and International Agreements. This section presents a simplified analysis of a dynamic model of a climate club and describes an alternative approach that analyzes supportable policies in climate agreements or climate clubs. Here is the basic idea: many activities have the characteristics of public goods in which the benefits are diffuse (have some elements of nonexclusivity and nonrivalry). The classic example is a lighthouse (or a Global Positioning System in the modern era), in which beacons or locations enjoyed by one do not exclude others.

Public goods create a challenge because they are prone to free riding, where some users may enjoy the benefits (light or location in the example just used) without paying. Governments solve the public goods problem using their powers of taxation to finance public works such as lighthouses and satellites. For the case of private activities such as recreational and sporting facilities, people can join together in clubs, which are a mechanism that allow voluntary agreements to provide goods with public-good characteristics ("club goods"). A club is a voluntary group deriving mutual benefits from sharing the costs of producing an activity that has club-good characteristics. The gains from a successful club are sufficiently large that members will pay dues and adhere to club rules in order to gain the benefits of membership.

The major conditions for a successful club include the following: 1) there is a public good–type resource that can be shared (whether the benefits from a treaty or the enjoyment of a golf course); 2) the cooperative arrangement, including the cost, is beneficial for each of the members; 3) nonmembers can be excluded at a relatively low cost to members; and 4) the membership is stable in the sense that no member wants to leave. For a thorough discussion, see ref. 17.

From an analytical point of view, international treaties can be viewed as clubs. Under the central principles of modern international law, nations are sovereign and have the fundamental right

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of political self-determination. In accordance with the 1969 Treaty of Vienna, a treaty does not create either obligations or rights for a third State without its consent. All international agreements are therefore essentially voluntary.

Given the structure of treaties, we can look to the characteristics of clubs to understand what can provide durable international agreements. The most important ingredients are that a public goods treaty, first, imposes costs on participants and, second, has sufficient deterrents for nonparticipants that the agreement is stable or self-enforcing.

As examples, the current international trade system provides access to other countries' markets with low trade barriers while providing access to the home market. For military alliances, the benefits are peace and survival, while the costs are military spending. The European Union (EU) is the most relevant example of a multinational club, with the benefits of a single market and the costs being elements such as regulatory uniformity and adherence to a unified climate policy. In all cases, countries must contribute dues—these being low trade barriers for trade or burden sharing in defense treaties. The requirement for a successful international system to deal with climate change can look to the theory and practice of clubs for its inspiration.

Agreements on global public goods such as climate change face greater challenges than club goods such as international trade agreements and military alliances because nonparticipants benefit from the actions of participants in climate agreements. The proposal here is to use linkages with other agreements (in this example, those relating to international trade) to convert a pure public good into a club good. The key point is that there are limits on the power of the linkage because there must be sufficient economic benefit or surplus in the linked agreement to "support" turning a global public good into a club good.

Modeling Supportable Policies in a Climate Club. The earlier analysis in ref. 1 found that it would be difficult to induce high participation with a carbon price well above \$50 per ton of CO_2 in a one-shot climate game. The full solution for a multiperiod, multiregion climate club appears computationally impossible with combinatorial or genetic algorithms, so the present study uses a different approach, which is the analysis of supportable policies. These are ones that are on the frontier of what can be supported by the club sanctions for nonparticipation. More specifically, the study analyzes "supportable policies," which are climate policies that can be supported by reasonable penalty tariffs (up to 10% uniform tariff).

The model is a standard economy–climate integrated assessment model that has been modified to estimate the supportable or maximum carbon price (or alternatively supportable maximum emissions reductions). This requires modules for economic growth, CO_2 emissions, international trade, climate damages, and the cost of emissions reductions. Except for trade, these equations come from the DICE-2016R3 model (18), while the trade equations come from ref. 1. The representative region is assumed to optimize its economic welfare (roughly, the present value of its full consumption including abatement costs and damages). The key assumption is that the emissions reductions and carbon prices are set at levels at which the region is indifferent about whether or not to join the club. In other words, it optimizes its behavior assuming that the cost of the trade sanctions is equal to the cost of abatement required by being in the club. For those familiar with integrated assessment models of climate change, the only novel feature of the modeling is to impose the breakeven constraint between abatement cost and trade penalties, which allows the calculation of supportable policies.

Focusing more closely on country decisions, each region's policy involves two decisions: each period's level of abatement and decisions about whether to participate in international agreements. If the agreement is a club-type agreement, each country will compare the costs of the penalty tariffs (if out of the club) against costs of the abatement (if in the club). At the breakeven point, as shown in *SI Appendix* and suppressing the time subscripts, the supportable carbon price (τ), emissions (E), and emissions control rate (μ) are given by the following equations.

$$\tau* \;=\; (\lambda_i \bar{p}_i/\sigma_i)^{1/2} \qquad [1]$$

$$\mu_i^* = (\lambda_i/\bar{p}_i\sigma_i)^{1/2} \qquad [2]$$

$$E_i^* = Y_i\sigma_i[1-(\lambda_i/\bar{p}_i\sigma_i)^{1/2}]. \qquad [3]$$

The variables are $\lambda_i = 2z_i\rho_i\theta T$, in which ρ = welfare impact of tariffs, z_i = openness ratio (trade/gross domestic product [GDP]), θ = club size (fraction of emissions in club), T = penalty tariff rate, $\bar{p}_i$ = cost of backstop technology, $Y_i = GDP$, and $\sigma_i = E_i/Y_i$.

Note that the supportable emissions control rate can be negative depending on the factors on the righthand side of Eq. **2** (e.g., with a high penalty tariff or a low backstop cost).

By calculating the growth rates, we see that the key variables change at one-half the rate of the growth of parameters such as the tariff rate, the rate of growth of carbon intensity *(*σ*)*, the rate of decline of the backstop cost, and the rate of growth of trade openness.

A key result of Eqs. **1**–**3** is that the supportable emissions control rate evolves over time with technological and policy parameters. The key ones that appear are technological improvements that lead to lower costs of noncarbon substitutes for fossil fuels. These will raise the supportable control rate and emissions reductions. While this point is central to the effectiveness of climate clubs, only empirical club modeling can indicate the actual importance of different factors. *Modeling Details* provides insights from empirical modeling.

Modeling Details. The estimates in this study are based on an empirical dynamic optimization approach using the standard DICE model with trade sanctions included, the TDICE model (see refs. 18 and 19 for a description of the DICE model). This TDICE model represents the idea that we are integrating the standard DICE integrated assessment model with a trade component. The approach is simplified and primarily intended to illustrate the power of a climate club plus enhanced decarbonizing technology to provide the glue for an international climate agreement. In what follows, "decarbonization" refers to the decline rate in the ratio of CO_2 emissions to output.

Here is the basic setup. The analysis begins with the standard DICE model with two modifications. One is to change the structure so that the abatement will represent the optimal behavior of a "representative country." This step involves changing the damage parameter to reflect the global public goods character of climate damages.

The second modification is to add a module that represents the costs and benefits of joining the climate club. This involves new equations and parameters that incorporate international trade and tariffs as well as a structure in which the costs of trade sanctions can be weighed against the costs of abatement. In the theory described in the last section and the empirical model, the country decides whether to join the club with costly abatement or to stay out of the club and incur costly trade penalties. This version assumes no retaliation by regions out of the club, and that assumption is reviewed in *Impact of Club Size*.

The model calculates the supportable target carbon price, emissions reductions, and emissions for the representative

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country. Prices are calculated as the dual variable (shadow price) on the emissions constraint. The supportable policy comes where the cost of abatement just equals the cost of the trade sanction. Abatement costs are proportional to output and to a polynomial function of the emissions control rate. The cost function is calibrated to more detailed models such as those in the Modeling Uncertainty Project model comparison study (20) and has been robust through several revisions.

We can interpret the supportable policies as the strongest incentive-compatible climate policy within the club. Policies that have lower target carbon prices obviously have lower abatement. Prices that are higher than the supportable carbon prices induce countries to drop out of the club and therefore have lower abatement. A further discussion of the parameters and their sources are contained in *SI Appendix*, section II.

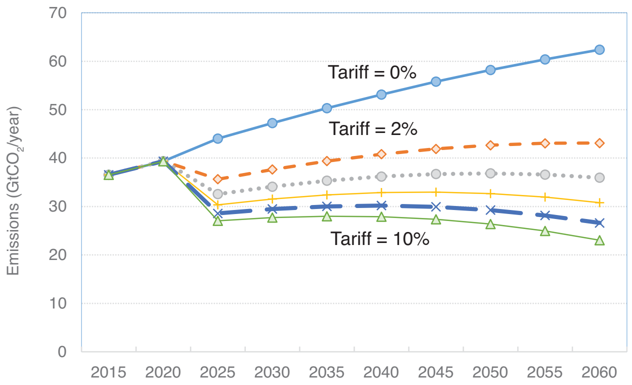

Fig. 1. Sustainable CO$_2$ emissions with base parameters and alternative penalty tariffs. The paths show the time paths of sustainable emissions (or maximum emissions reductions) that are incentive compatible for different club penalties. The paths from top to bottom are penalty tariffs of 0, 2, 4, 6, 8, and 10%. The higher tariffs are compatible with stronger abatement because the economic costs of the tariffs are higher; the value of belonging to the club is therefore higher with the higher tariff. Other parameters (such as technology policies, size of club, and openness) are at base values.

Modeling Results for Dynamic Aggregative Climate Club

Objectives of Climate Policy. The purpose of a climate club is to design a structure that leads to the ultimate policy objectives. We discuss two primary objectives. One is the cost–benefit "optimum" from earlier runs of the DICE model. This run stabilizes the global mean temperature at about 3 °C by the end of the century. To attain the optimal path requires stabilizing emissions at 30 to 40 billion tons of CO$_2$ emissions per year by mid–21st century depending on the damage function.

A second standard, adopted by countries and increasingly used as a target in policy and analysis, is limiting temperature changes to 2 °C above preindustrial levels, this being the "two-degree limit." The two-degree limit requires attaining zero net greenhouse gas emissions around or shortly after mid–21st century with negative emissions after that.

Each of these two approaches has arguments on its behalf. Those points will not be reviewed here. Rather, the point is to determine whether the climate compact will achieve either or both objectives and under what conditions.

Assumptions in the Different Calculations. This section contains the results of the TDICE modeling of the dynamics of climate clubs. The parametric assumptions are contained in Table 1. The table shows the assumptions for the "base parameters" of no club (no international agreement) as well as three alternative policies from low policy to high policy. The policies reflect both different penalties built into the club (in terms of the penalty tariff rate) and rates of technological change (reflecting the strength of technology policies). The last three rows show the assumptions for the other major structural parameters. The other parameters are not varied in the different policy runs.

Results for Base Parameters. Before presenting the numerical projections, it must be emphasized that the estimates suggest a greater precision than integrated assessment models can normally deliver. Unlike statistical estimates, simulation and optimization models cannot easily calculate the SEs of estimates or predictions. Models are for insights and not exact answers.

We will begin with the results of the base parameters. These can be interpreted as ones in which all parameters of the TDICE model are at their base or most likely levels, with no induced technological change or programs to speed the development and introduction of low-carbon technologies. Fig. 1 shows the sustainable emissions with base parameters and with alternative penalty tariff rates from 0 to 10%. This analysis assumes that a uniform tariff of 10% is the maximum that is consistent with maintaining the current world trade system. It also sets aside issues of compatibility of the particular penalty instrument with national laws and treaties.

The path associated with a 0% tariff is a baseline path with rising emissions and shows the result of a free-riding equilibrium. The highest penalty tariff with base technology stabilizes emissions at a little below 30 GtCO$_2$/year, but it does not reach zero emissions by 2060. This suggests that a climate club with current technological change can achieve the cost–benefit optimal path in the next half-century, but it cannot achieve the more ambitious objective of the two-degree target.

Rapid Technological Change. The analysis in the first theoretical analysis suggested that sustainable emissions reductions could be more ambitious with more rapid technological change. There are two possible routes for rapid change. One is to lower the cost of substitute technologies. This is represented as lowering the cost of the backstop technology.

Table 1. Assumptions on major parameters for TDICE model

Parameter or policy	Base parameters	Range of values	Low policy	Medium policy	High policy
Uniform penalty tariff rate	0.0051%	0.0051–10%	5%	10%	10%
Fraction of world in club	50%	10–90%	50%	50%	50%
Technological features					
Decline backstop cost per year	1.0%	1–4%	1.0%	2.0%	4.0%
Rate of decarbonization per year	1.5%	1.5–3.5%	1.5%	2.5%	3.5%
Structural parameters					
Ratio national to global social cost of carbon	10%	5–10%	10%	10%	10%
Annual growth rate openness	1%	0–2%	1%	1%	1%
Welfare loss of tariffs, percent of national income at 10% tariff	0.40%	No variation	0.40%	0.40%	0.40%

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The backstop technology is a set of technologies that can produce zero net carbon emissions at minimum cost. For example, it might be a combination of renewable technologies, minimal fossil energy, and direct air capture that offsets any fossil energy emissions. The estimate here is that the backstop technology is available by the mid–21st century at a cost of about \$500/tCO$_2$ in 2020 US dollars. As discussed in *SI Appendix*, we investigate the impact of policies that would lower the cost of the backstop (substitute) technologies at 2% per year and 4% per year. A lower cost of the backstop technology by about 30% would be virtually equivalent to a more rapid decline in the cost of the backstop technology of 1 percentage point per year. Additionally, the study investigates alternative rates of decarbonization. The base rate is –1.5% per year. The two alternatives are rates of −2.5 and −3.5% per year.

Fig. 2 and Table 2 compare the supportable policies with different policies and technological assumptions. The case with a zero tariff and no technology is the standard DICE model with base technological change and no climate club. Not surprisingly, this shows continued growth in global emissions, reaching 59 GtCO$_2$/year in 2050.

The second and third cases give roughly the same answer as to supportable emissions. These are ones 1) with no club policy and rapid technological improvement and 2) with strong club policy and current technological improvement. Each of these leads to slowing of emissions by the mid–21st century, 33 and 27 GtCO$_2$/year in 2050. Both fall far short of zero net emissions.

The final case is strong club policy with rapid technological improvement. This policy shows rapid decline in emissions, reaching zero net emissions by midcentury with −3 GtCO$_2$/year in 2050.

So, the simple conclusion here is that without either a strong club or very rapid decarbonizing technology, emissions will stabilize but not decline sharply. Either a strong club or rapid decarbonizing technology will lead to slight declines in emissions. Only a maximal effort to improve noncarbon technologies along with strong incentives to join an international agreement can produce zero emissions by mid–21st century.

Impact of Club Size. An important issue is the impact of different size clubs on the incentives to participate. For example, a small club will have little leverage because the penalty tariffs will have only a small economic impact on nonparticipants. Conversely, a large club that covers most countries will have maximal power to induce countries to participate.

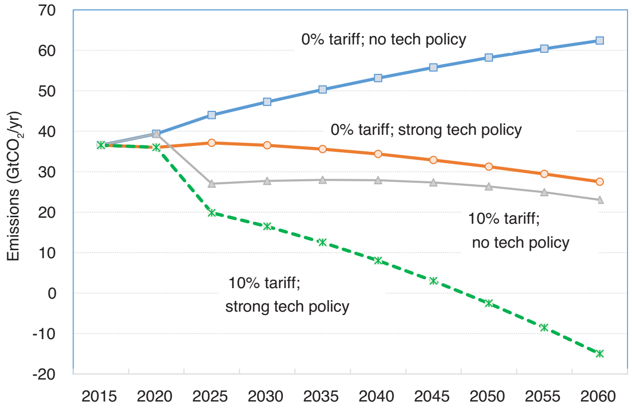

Fig. 2. Supportable emissions for alternative technology policies and club policies. The figure shows the impact on sustainable emissions for four pairs of club tariffs and technology policies. The top line shows current international policies of no club (zero penalty tariff) and no technology policies. The bottom line shows the supportable emissions with both strong club and strong technology policies. Intermediate paths are no club policy and strong technology (second line from top) and strong club and current technological trends (third line from top).

Table 2. Interaction technological policies and the climate club

Policy scenario	Emissions, 2050 (GtCO$_2$/y)
No policy, base technologies	59.4
No policy, strong technologies	32.6
Strong club, base technologies	26.5
Strong club, strong technologies	−2.5

A key question for the club is the potential for trade retaliation. The problem is particularly severe for small clubs. If a single small region creates a climate club, then other countries can offset any penalties through actual or potential retaliation. On the other hand, with large clubs, countries that are outside the club will have little leverage to offset penalty tariffs, especially if they are small and act individually.

The study in ref. 21 shows in a stylized model with trade retaliation that the potential for a club-type system with trade linkage depends upon the relative gains of trade and climate abatement. It also shows that there is a tipping point in participation in which a threshold number of participants leads to the full cooperative equilibrium. A recent empirical study (15) explicitly models a club with a potential for retaliation but with several differences from the current approach. In a simplified analysis, they find a similar tipping result to ref. 21. Estimates in ref. 15 show that a core club of the EU and United States will induce other countries to join until all regions are in the club. The intuition here is similar to Robert Keohane's "hegemonic stability," in which a powerful country or group is able to set standards for other countries, seen for example in the Bretton Woods institutions. These results emphasize that issues of retaliation are core issues that need to be dealt with not only through providing incentives to join the club (through a large club) but also through modifying trade agreements with a set of "climate amendments" as described in ref. 1.

Assuming there is some threshold beyond which retaliation is deterred, we can examine supportable policies for different club sizes. The results are shown in *SI Appendix*, Fig. S1 for 2050 supportable carbon prices, for an assumed minimum sustainable club size of one-third of emissions, and using strong policies in Table 1. The results show that the sustainable price rises sharply with larger clubs as is shown by the mathematics in *SI Appendix*.

The strong incentive of large clubs is an encouraging feature, suggesting that a core group of countries can start the process rolling. This point is indeed the opposite of the current climate negotiations in the Conferences of the Parties which are based on the principle of unanimity. In terms of the club theory, the current arrangement means that a single holdout can stymie a coalition and leave the world stuck with the ineffective international agreements of the last two decades.

Impact on Temperature. The TDICE model is not primarily designed to project climate over the coming decades. However, projections using the climate module in the DICE model find that the strong club policy will have the effect of limiting temperature increase over the coming century. The strongest policies and technologies will keep temperatures just within the 2 °C target. However, either weak club policies or current technological improvement is likely to lead global temperature increase to the 3 to 3 1/2 °C range by 2100. Base technologies and no policy would lead to slightly more than 4 °C in 2100, with a continued rise after that. The results on global

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temperature are shown in *SI Appendix*, Fig. S2. See the caveat in *SI Appendix* on the trajectories for different targets.

Induced Innovation. Before concluding, it is important to emphasize a critical shortcoming of the modeling here and in most other integrated assessment models. Virtually all studies assume that technological change is unaffected by climate policy—or, in technical terms, they assume exogenous technological change. History and empirical studies show conclusively the importance of prices and market size on the rate and direction of technological change for standard goods and inputs (see particularly refs. 22–24). However, with a tiny number of exceptions, implementing an empirically based strategy for introducing endogenous technological change has proved elusive.

Since part of the rationale for the climate club is to raise carbon prices and high carbon prices would be a strong incentive for carbon-saving technological change, we can test for the impact using results from earlier studies. Results from refs. 22–24 have found that the emissions reduction from induced innovation is about half of that of substitution at a 50- to 100-y time horizon. I therefore implemented a simple two-stage procedure to test the implications of this result. I ran the standard case for a penalty tariff of 10%. I then calculated the impact on the rate of endogenized decarbonization using the benchmark effect just described. The result was an increase of the rate of decarbonization by about 1/2% per year. It reduced 2050 emissions from 26 to 20 $gtCO_2$/y, thus moving toward the zero-emissions target. The results of the calculations are shown in *SI Appendix*, Table S1.

This estimate provides a hint at the role of carbon pricing in promoting innovation and providing further incentives toward strong climate policies. At the same time, it must be emphasized that the empirical basis for estimating the magnitude of the boost to low-carbon innovation from higher carbon prices is very sparse. Since the role of pricing in externality markets is radically different from that in standard markets, the impact on innovation in externality markets might be much larger than that in standard markets (*SI Appendix*, section III).

Data Availability. All study data are included in the article and/or *SI Appendix*. The major results are produced by the TRICE model GAMS code, available at the end of *SI Appendix*. The GAMS code can be run in the GAMS software code or with some modifications in R. The numerical results are available in an output "put" file produced when running the program.

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