CLIMATE CLUB FUTURES: ON THE EFFECTIVENESS OF FUTURE CLIMATE CLUBS

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Climate Club Futures:
On the Effectiveness of Future Climate Clubs

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Abstract

A proposal to combat free-riding in international climate agreements is the notion of a "climate club" or coalition of countries 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 results suggested that there were limits on the potential strength of clubs and that it would be difficult to have deep abatement strategies in the club framework. The current work extends the single-period approach to many periods and develops an approach analyzing "supportable policies" to analyze multi-period clubs. The major surprise of the study is the interaction between the club structure 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 highly costly abatement; similarly, rapid technological decarbonization by itself will not induce deep abatement because of country free-riding. But the two together can achieve the international objectives.

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I. *Background*

Early research on climate clubs

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 it is at the heart of the failure to deal with climate change. Without an appropriate structure, no single country has an incentive to cut its emissions sharply. Moreover, if there is an 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 *non-cooperative 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 no stick at all.

One proposal to combat free-riding is the notion of a "climate club" or coalition of countries to encourage high levels of participation and abatement. The idea, analyzed in Nordhaus (2015), 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 nations would be penalized if they did not meet their 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 Weitzman 2015.) 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 2020 and rise over time at, say, 3% per year in real terms.

Additionally, both theory and history suggest that some form of sanction on non-participants is required to induce countries to participate in agreements with local costs but diffuse benefits (see particularly Barrett 1994, 2003). While the exact degree of free-riding and cooperation will differ according to 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 (Carraro and Siniscalco 1993, Chandler and Tulkens 1995, Bosetti et al. 2012, Lessmann et al. 2015, Keohane and Victor 2016). Studies of club-like structures can be found in Gollier and Tirole (2015), Cramton, Ockenfels, and Stoft (2017), Böhringer, Carbone, and Rutherford (2016), Keohane, Petsonk, and Hanafi (2017).

The proposal in the climate club was a uniform tariff on all imports of non-club countries into the club. Take as an example a penalty tariff of 5%. If non-participant country *A* exports $100 billion into the club region, it would be penalized by $5 billion of tariffs. In estimates of the coalition stability of a one-shot climate club using the C-DICE model, Nordhaus (2015) estimated that climate clubs would be extremely effective (relative to no club) for low carbon prices. However, the modeling suggested that it would be difficult to support carbon prices above $50 per ton of CO_2 with the economic structure of the current period (2011 in those estimates).

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.[2] The present study tackles the more complex question of sustainable climate clubs in a multi-period framework.

Major results

Here are the major results. *The major tool used here is the concept of a supportable policy, whether emissions price, emissions limit, or other constraints on producer and consumer behavior.* 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 other ones). The most important example is a supportable carbon price. Policies that have target carbon prices lower than the supportable price have lower abatement; policies with higher

[2] The original model had 15 regions reflecting actual economic and environmental data. Finding a stable coalition is combinatorial in nature, and its solution is thought to be in the class of NP-hard problems. There appears to be no efficient algorithm for calculating stable coalitions, and current algorithms claim reasonable results in time $O(n2^n)$. In principle, we would need to take each of the 2^n coalitions and determine whether they are stable against all the other $2^n - 1$ coalitions, which requires about $2^{2n} \approx 10^9$ comparisons for 15 regions. While this is computationally feasible with supercomputers, it is unnecessarily burdensome, particularly for model construction and comparison of regimes. The earlier calculations relied on an evolutionary algorithm to find stable coalitions. Experiments indicate that stable coalitions are usually found within 100 iterations. A full dynamic analysis with multiple periods would require > 10^{100} comparisons and was beyond the capability of the analysis.

target carbon prices induce countries to drop out of the club and therefore also have lower abatement (as countries move to their national targets, which are substantially lower and essentially zero). The study defines supportable targets, shows how to find them in a simple example, and then develops a model which allows calculation of supportable policies over time.

A second contribution is to develop a simple analytical model of the supportable participation of a party in a regime (such as a climate club) that imposes costs but also conveys rewards for participation (or avoids punishments for non-participation). While estimating the equilibrium of a coalition in a dynamic framework is computationally extremely burdensome (as noted in footnote 2), determining supportable policies is relatively simple, both analytically and computationally. The simple analytical model below shows that the time path of supportable policies for the climate club depends primarily on six determinants: 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 third contribution is developing a simple global computable model (Trade DICE or TDICE) for estimating the supportable carbon prices, emissions, as well as the geophysical variables such as concentrations and temperature. The model uses much of the structure of the standard DICE model (described below), but adds equations that represent the "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 where the costs of participating (through abatement) just equal the costs of non-participation (the trade sanctions).

Fourth, the results of the TDICE model show several features. To begin with, in the baseline-parameter scenario for technology and openness, even with strong trade sanctions of 10% uniform tariffs for non-participation, *emissions are slowed sharply in the club relative to no 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 27 $GtCO_2$, rather than the target of zero. Global temperature in 2100 reaches 3.1 °C rather than the 1.5 or 2 °C targets. This result confirms the statement in Barrett (2018) that the climate club as originally conceived is insufficient to attain international objectives.

A fifth finding shows the importance of the *combination of the club incentives and rapid decarbonizing technological change.* As mentioned above, two important parameters in the analysis are the rate of decarbonization and the rate of technological change in the backstop technology. These 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 0% in the base assumption). With these assumptions along with the strong tariff incentive of 10% penalty tariff, global emissions in the TDICE model hit zero by 2050 and global temperature has a maximum of 1.9 °C. While the combination of a strong club and rapid technological change are at the outer edge of realism, they do point to a potential political-economic-technology mechanism for attaining ambitious climate objectives.

A sixth finding comes from developing a regionalized version of the model (TRICE, or Trade and RICE). The model is only a sketch of a full regional model but allows us to *investigate the impacts of regional differences in features such as carbon intensities and costs of abatement on supportable policies.* The TRICE approach indicates that supportable carbon prices differ markedly across regions. Taking 2020 as an example, the range is from a low of \$72/tCO_2 for Russia, almost as low for China of \$86/tCO_2, to \$285/tCO_2 for Sub-Saharan Africa. Russia has a low supportable price because of its high carbon-intensity, with the converse for Sub-Saharan Africa. The impact of regional heterogeneity, as seen by comparing TDICE and TRICE, is to lower the global supportable carbon price and supportable emissions reductions. The reason is that some of the countries with the largest emissions, particularly China and the US, have relatively low supportable carbon prices.

A seventh finding concerns the "carbon price Laffer curve." This shows the relationship between the target carbon price and total emissions reductions. It is hump-shaped: at a carbon price of \$0, there are no emissions reductions, while at extremely high carbon prices, there is zero participation. *Using the TRICE model, we calculate the carbon price Laffer curve for 2050 has peak emissions reduction at \$100/t*CO_2 *for the 5% tariff and \$160/ton for the 10% tariff.* Figure 5 shows the point graphically.

Finally, *the major surprise of the study is the interaction between the club structure and rapid decarbonizing technological change.* 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 produce highly costly abatement; similarly, rapid technological decarbonization by itself will not induce deep abatement because of country free-riding. But the two together – providing incentives to participate but at the same time lowering the costs of participation – are a team that, in principle and according to simple modeling, can achieve the international objectives.

II. Analytical extension of climate clubs for many periods

Clubs and international agreements

We begin with a simplified analysis of a dynamic model of a climate club. The present study develops a new approach to the issue by analyzing "supportable" policies in climate agreements or climate clubs. Here is the basic idea. Many activities have the characteristics of public goods, where the benefits are diffuse, or more precisely have some elements of non-exclusivity and non-rivalry. The classic example is a lighthouse (or a GPS in the modern era), where none are excluded, and where the beacons enjoyed by one do not crowd out or exclude others.

Public goods create a challenge because they are prone to free-riding, where some users may enjoy the benefits (light) without paying. Governments solve the public-goods problem using their coercive powers of taxation to finance public works like lighthouses. For the case of private activities, such as recreational or sporting facilities, people can join together in clubs, which are a mechanism that allow *voluntary* agreements to provide public goods. What is a club? A club is a voluntary group deriving mutual benefits from sharing the costs of producing an activity that has public-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) that 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) that the cooperative arrangement, including the cost, is beneficial for each of the members; (3) that non-members can be excluded or penalized at relatively low cost to members; and (4) that the membership is stable in the sense that no one wants to leave.

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 of political self-determination. The current system requires that countries consent to joining international agreements ("A treaty does not create either obligations or rights for a third State without its consent." Treaty of Vienna, 1969, article 34). 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 non-participants 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. 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.

Modeling supportable policies in a climate club

The earlier analysis in Nordhaus (2015) 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 analysis of a multi-period climate club appears computationally impossible with combinatorial tools, 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 non-participation. More specifically, the study analyzes "supportable carbon prices," which are carbon prices that can be supported by reasonable penalty tariffs (up to 10% uniform tariff).

Here is the basic analysis. A rational economic analysis by each country will involve a comparison of the costs of the penalty tariffs (if out of the club) against costs of the abatement (if in the club). We can write the two terms as follows for a typical country. Begin with the losses from the trade penalty for countries who are non-participants:

(1) Trade loss$_i$ = $\theta T z_i Y_i \rho_i$

where θ = participation ratio of countries in the club, T = tariff rate,
z = ratio of trade to GDP, Y_i is GDP, and ρ = welfare loss per % tariff rate.

The parameters with a subscript *i* refer to country parameters, while those without a subscript are either outside the control of countries (e.g., other countries' participation decisions) or rules of the climate club (e.g., the target carbon price and the penalty tariff rate). Equation (1) shows the welfare losses from the penalty tariffs. The first four parameters on the right are observable data and pose no difficulty. However, the welfare impact of trade is extremely complicated and controversial. The research here relies on Ossa's calculations as discussed in Nordhaus (2015), see particularly the appendix. The welfare loss is close to linear up to a tariff rate of 10%, so it is taken as linear for the present analysis.

The second term is the abatement cost for countries who are participants. In the simplified model in Nordhaus (2015), abatement cost is the following:

(2) Abatement cost = $\alpha_i \mu_i^{\beta} Y_i$

where α_i = abatement cost parameter in current period, β = parameter of the cost function, and μ_i = emissions control rate.

In the earlier analysis, β = 2, and that will be followed in the analysis of this section. The marginal cost of abatement is equalized to the carbon price, which yields:

$$\tau = 2\alpha_i \mu_i Y_i (\partial C / \partial E) = 2\alpha_i \mu_i / \sigma_i$$

(3) $\mu_i = \tau\sigma_i / (2\alpha_i)$

where τ = marginal cost of abatement and the carbon price or carbon tax in a market context, and σ = emissions / output ratio.

Putting (3) into (2) yields:

(4) Abatement cost = $\alpha_i (\tau\sigma_i / 2\alpha_i)^2 Y_i = \sigma_i^2 \tau^2 Y_i / 4\alpha_i$

This can be simplified by substituting in the cost or carbon price of the backstop technology, $(\bar{p})$. This represents the carbon price at which emissions are zero and the emissions control rate is 1. This is obtained from equation (3) by setting μ = 1, which yields $\bar{p} = 2\alpha_i / \sigma_i$. Substituting into (4) yields:

(4') Abatement cost $= \alpha_i(\tau\sigma_i / 2\alpha_i)^2 Y_i = \sigma_i \tau^2 Y_i / \bar{p}^2$

Many of the parameters are observable ones. GDP and CO_2 emissions are reported more or less accurately by countries today. The target carbon tax rate is a design parameter of the climate club. The cost of the backstop technology is highly uncertain but been the subject of detailed research. Note that the uncertainties about the parameters are issues that arise for countries in deciding whether to participate but are not important for the impact of the program on emissions and climate change.

The dividing line between participation and non-participation is "supportable international target carbon price," or the target carbon price at which the cost of abatement exactly equals the welfare cost of the penalty tariff. Equation (5) shows the dividing line where the cost of abatement just equals the cost of the tariff. Equation (6) then solves for the supportable carbon price as a function of the parameters.

(5) $\theta T z_i Y_i \rho_i = \sigma_i \tau^2 Y_i / \bar{p}^2$

or

(6) $\tau^* = \bar{p}(\theta T z_i \rho_i / \sigma_i)^{-1/2}$

We can also write this in terms of the supportable emissions control rate, μ^*. Equation (7) equates the two costs using equations (1) and (2). Equation (8) then solves for the supportable control rate.

(7) $z_i \rho_i \theta T_i = \alpha_i \mu_i^{*2}$

or

(8) $\mu_i^* = (2 z_i \rho_i \theta T / \bar{p}_i \sigma_i)^{-1/2}$

A final result is for supportable emissions. Using (8), we have

$E_i = \sigma_i Y_i (1 - \mu_i)$

For simplicity, set $Y_i = 1$. Then we have supportable emissions using (8):

(9) $E_i^* = \sigma_i (1 - (2 z_i \rho_i \theta T / \bar{p}_i \sigma_i)^{-1/2})$

Equations (6), (8), and (9) indicate that the supportable carbon price, emissions, and the emissions-control rate change over time as a function of the parameters of the economy. Equation (8) is easier to interpret and will be used in what follows.

Begin by taking the time derivative of the logarithm of (8) and denote the variable $\hat{x} = d[\ln(x)]dt$.

(10) $\hat{\mu}_i^* = 0.5(\hat{z}_i + \hat{\rho}_i + \hat{\theta} + \hat{T} - \hat{\bar{p}}_i - \hat{\sigma}_i)$

According to (9), the supportable emissions control rate grows at half of the rate of growth of the different parameters: the ratio of trade to GDP (z_i), the welfare loss per % tariff rate , the penalty tariff rate *(T),* and the participation rate (θ). The supportable emissions control rate declines at half of the rate of decline of the cost of the backstop technology $(\bar{p}_i)$ and of the carbon-output ratio (σ_i). Also, hardly surprising, the strength of the penalties (here, the tariff rate) increases the strength of the system. Note that in the simplest model, output growth does not enter the final equations.

The impact of parameters on supportable emissions is non-linear. Calculations show that the elasticities of supportable emissions at a 50% emissions control rate with respect to σ, T, and $\bar{p}$ are, respectively, -1.5, -1.0, and -0.5.

One important insight here, which will be seen important in the empirical estimates, is the role of technology in strengthening the club. The two technological parameters are the cost of the backstop technology (productivity growth in renewables) and the rate of exogenous decarbonization (which can operate through many factors such as energy efficiency or conservation). These are important factors in strengthening the power of the club mechanism.

The analysis can provide qualitative results, but only empirical club modeling can answer the question of the feasibility of climate clubs for inducing deep emissions reductions. The next section provides insights from empirical modeling.

III. Empirical modeling of participation with trade sanctions

Overview

This section moves to a dynamic optimization approach using the standard DICE model with trade sanctions included (see Nordhaus 2017 for a description of the DICE model). This is called the Trade-DICE, or TDICE model, representing the idea that we are integrating the standard DICE integrated assessment model with a trade component. I emphasize that the exercise is extremely simple, in the spirit of the analytical approach above, and primarily intended to illustrate the power of a climate club to provide the glue for an international climate agreement.

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

The second modification is to add the trade module. As in the example above, the country decides whether to join the club with costly abatement, or to stay out of the club and experience costly trade penalties.

The model calculates the *supportable* target carbon price, emissions reductions, and emissions for the representative country. The supportable policy is one where the cost of abatement just equals the cost of the trade sanction. We can interpret the supportable policies as the maximum possible club policy. Policies that have lower target carbon prices obviously have lower abatement. Higher target carbon prices induce countries to drop out of the club and therefore have lower abatement (as countries move to their national targets, which are substantially lower and essentially zero).

Model details for TDICE

This section describes the structure of the TDICE model. I assume that people are familiar with the DICE model, which is a global model linking population, total factor productivity, investment, output, emissions, concentrations, climate, impacts, and policy. The TDICE model has two major changes from the standard DICE; each will be explained after they are described.

1. The first change is to change the model from a global model to a model of a representative country.
2. The second change is to introduce trade sanctions so that each country can weigh the cost of reducing CO_2 emissions if in the club against the trade sanctions if not in the club.

Representative country. To transform the global DICE model into a stylized regional model requires primarily changing the damage structure. I assume that there are ten identical countries each of which is 10% of the global economy. The outcome would be identical to the global model if there are no externalities. To incorporate the climate externalities, it is necessary to reduce the damages by 90% to reflect the fact that each country gets only 10% of the damages. If the model is optimized with the smaller damages, the outcome is almost exactly the same as the Nash non-cooperative equilibrium in a multi-region model. Each country has the same structure as the global economy but has only 10% of the damages. By reducing the damage rate to one-tenth of the global total and keeping all other parameters the same, we can mimic the behavior of a representative country behaving non-cooperatively (i.e., maximizing its own welfare).

Trade sanctions. The other major change is to introduce trade sanctions for countries that do not meet the target-carbon-price objective. The formula for the cost is provided in equation (1) above. To calculate the supportable policies, we add a constraint that abatement cost equals sanctions cost, as shown in equation (5). The optimization is then to maximize welfare (quite close to minimizing cost) subject to the abatement cost equal the trade-sanctions cost. In GAMS language, the two key new equations are the following:

```
*Trade Equations
 TRCeq(t)..            TRC(t)     =e=  Openness(t)*Welfloss*Tariff*fracclub;
 Abatetradeeq(t)..     TRC(t)     =e=  Abaterat(t);
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Here *TRC(t)* = trade-sanctions costs as a fraction of output; *Openness(t)* = trade/output ratio; *Welfloss* = welfare lose per unit tariff; *Tariff* = uniform tariff rate; *fracclub*= fraction of global emission in club; and *Abaterat(t)* = abatement cost as ratio to output.

Algorithmics. The program is run for 19 periods (through 2100). The full model with 16 regions, 3 tariff rates, 3 rates of decarbonization, and 3 rates of backstop decline takes about 3 minutes. No issues of multiple equilibria or infeasibility were encountered.

Parameter estimates

The basic DICE model uses the DICE-2016R3 version. This was the 2016 model updated to 2018 prices and used in Nordhaus (2019). Major parameters were examined in early 2019 to determine whether there were significant changes. None were found, so the model was unchanged except for some adjustments to clean the code.

Preliminary tests indicated that six parameters would have major impacts on the estimates: These were openness (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, several parameters were found to be unimportant. These are the rate of growth of GDP, the ratio of national to global social cost of carbon, and the damage function. Other parameters of the DICE model were not tested.

Two of the six parameters have a historical record: the carbon ratio (CO_2/GDP, or σ_i in the analysis above and *sigma* in the modeling) and the openness ratio (Imports/GDP, or z_i in the analysis above and *openness* in the modeling). Since 1980, these have each been declining at about 2% per year. The openness ratio took a sharp drop after the 2008 financial crisis and has just recovered, while the carbon ratio has declined steadily over the last few years. For purposes of modeling, I assume that openness will resume a growing trend, but at a slower rate than the last half century, at 1% per year. The rate of decarbonization will be taken at the DICE model assumption of -1½%/year based on the most recent data. However, we emphasize that innovation policy can affect this ratio and examine two alternative values that increase decarbonization to -2½ %/year and -3½%/year.

Another critical policy parameter, but one without a strong empirical support, is the price of the backstop technology $(\bar{p})$.. This can be measured indirectly from abatement cost functions of the type shown in equation (2), but there are no persuasive data from which to observe the evolution of the backstop price. One possible approach is to examine changes in the price of renewable (or more precisely non-carbon) energy sources. Estimates in Fouquet (2018) indicate that the prices of solar and wind technology have declined at between 8 and 10% per year from 1980 to 2015. Nuclear energy costs have risen over the period, although the actual changes differ by country. Outside of electricity, the data are sparser, although there have been gains in transportation and heating. It should be emphasized that these gains have been largely in the context of zero carbon prices.

For the baseline estimates, I assume that the rate of decline of the cost of the backstop technology is 0.2% per year. I will examine two alternatives, decline rates 2% per year and 4% per year, to emphasize that the evolution of low-carbon technologies is an important component of an effective climate-change policy.

Three other parameters are quantitatively important: the tariff rate *(tariff)*, fraction of the world in the club *(frclub)*, and the welfare loss per unit tariff *(welfloss)*. The tariff rate is an important design features of the climate club. We test alternative tariff rates, but the outcome (as seen in the analysis above) is that the supportable carbon price is a function of the square root of the tariff rate.

The fraction of the world in the club *(frclub)* is an endogenous outcome variable that is a function of all the other variables. Nordhaus (2015) calculated these variables for alternative policies for a single year. The current research, however, cannot perform an analysis of stable coalitions, so the values of *frclub* vary from 10% to 90%. The 10% value measures whether the club is attractive when it is small, while the 90% value measures its stability when virtually all countries are members.

The welfare loss per unit tariff *(welfloss)* is a complicated structural parameter that is a function of output composition, trade policies, transportation costs, product heterogeneity, and other variables. We have taken estimates from Ossa (2015), as noted above. The results are sensitive to *welfloss,* but the parameter is not part of either trade or climate policy.

Before proceeding, it is important to emphasize a critical shortcoming of the modeling here (and in most other integrated assessment models). This is the exogenous feature of technological change. History and empirical studies show conclusively the importance of prices and market size on the rate and direction of technological change (see particularly Popp 2002, 2004). However, with a few 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 that would be a strong incentive for carbon-saving technological change, we can at this stage simply emphasize that *the impact of the club structure is undervalued in the modeling below because there is no automatic market or governmental innovative response to the changing carbon prices.* We envision further work on this issue, but that will have to wait for another day.

IV. Modeling Results for Dynamic Aggregative Climate Club

Begin with a word on targets. In the discussion below, we compare the results with two normative standards. One is the cost-benefit optimum from earlier runs of the DICE model. This run stabilizes temperature at about 3 °C by the end of the century. To attain the optimal path requires stabilizing emissions between 25 and 40 billion tons of CO_2 emissions per year by mid-21st century. A second standard, adopted by countries as a target, is limiting temperature change to 2 °C above pre-industrial levels, this being the "2-degree limit." The 2-degree target requires attaining zero emissions by mid-21st century, with negative emissions after that. Each of these two approaches has arguments on each side. Those will not be reviewed here. Rather, the point is to determine whether the club will achieve either or both, and under what conditions. These are oversimplified but reasonably accurate ways of considering whether a climate club can achieve the desired objectives.

This section contains the results of the TDICE modeling of the dynamics of climate clubs. The parametric assumptions are contained in Table 1. The base parameters use the assumptions from the standard DICE model with or without the club structure. The second column shows the range of assumptions. The last three columns contain assumptions about three different policy scenarios combining the strength of the club and technological change.

Parameter of policy	Base parameters	Range of values	Low policy	Medium policy	High policy
Carbon club design features					
Uniform tariff rate					
No policy	0.1%				
Club	5%	0.1 to 10%	5%	10%	10%
Fraction of world in club	50%	10% to 90%	50%	50%	50%
Technological features					
Decline backstop cost per year	0.2%	0.2% to 4%	0.2%	2.0%	4.0%
Rate of decarbonization per year	1.5%	1.5% to 3.5%	1.5%	2.5%	3.5%
Structural parameters					
Ratio national to global SCC	10%	5% to 10%	10%	10%	10%
Annual growth rate openness	1%	0% to 2%	1%	1%	1%
Welfare loss of tariffs, fraction of national income at 10% tariff	0.40%	No variation	0.40%	0.40%	0.40%

Table 1. Assumption on major parameters for TDICE model

Results for base parameters

Begin with the runs for the base values of the parameters. These can be interpreted as ones in which all TDICE values are at their current levels, with no induced technological change or programs to speed the development and introduction of low-carbon technologies. Figure 1 shows the sustainable emissions with base parameters and 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.

The path associated with 0% tariff is a baseline path with rising emissions. The highest penalty tariff stabilizes emissions at around 30 $GtCO_2$/year but does not meet a target path that would reach zero emissions by 2050. This suggests that a base-parameter climate club can achieve the optimal path in the next half-century, but it cannot achieve the more ambitious objective of the 2-degree target.

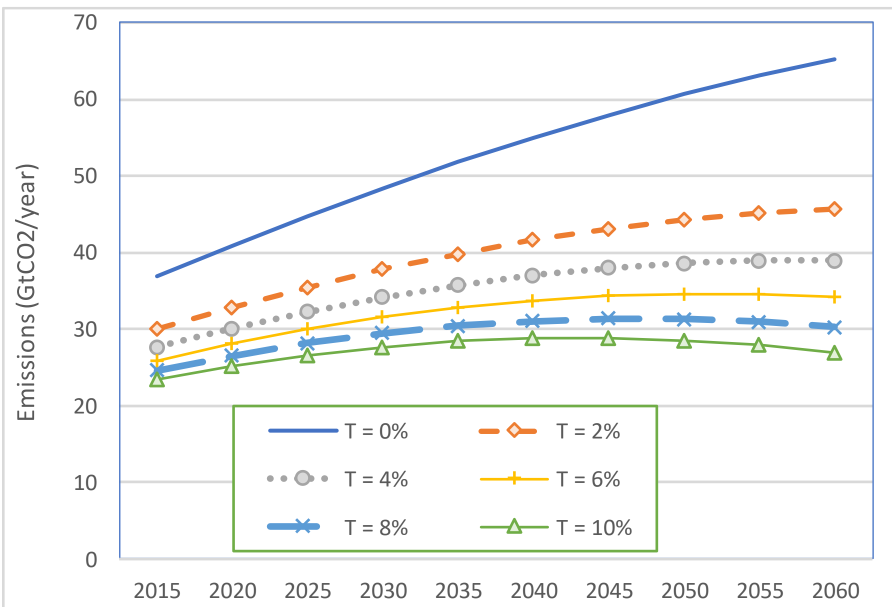

Figure 1. Sustainable CO_2 emissions with base parameters and alternative penalty tariffs

Rapid technological change

The analysis in the first section suggested that sustainable emissions reductions could be more aggressive 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 in the TDICE model as lowering the cost of the backstop technology. (The backstop technology is one that can replace all carbon fuels and is superabundant, assumed to be about $660 per ton of CO_2 currently.) As discussed above, we investigate the impact of policies that would lower the cost of the backstop (substitute) technologies at 2% per year and 4% per year.

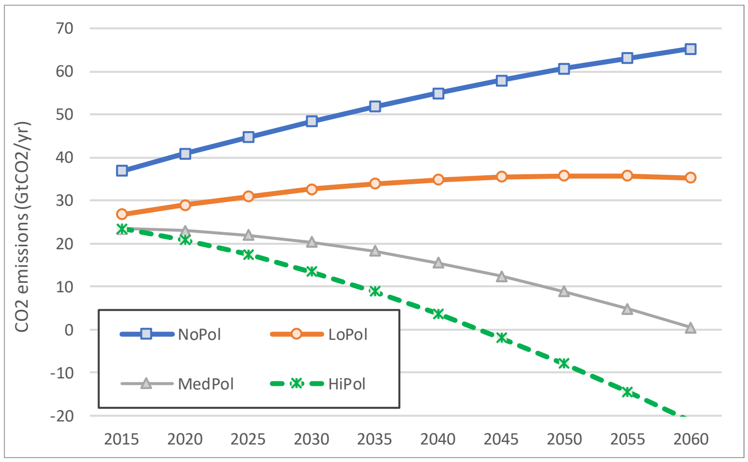

Figure 2. Supportable emissions for alternative rates of technological change and no-policy scenario

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Figure 2 compares the supportable policies for different technological assumptions. The "NoPol" is the standard DICE model with base technological change and no club. The policy scenarios are ones the three in the right-hand columns of Table 1: low policy, medium policy, and high policy. The low policy scenario has a moderate penalty tariff (5%) and the base technological assumptions. The medium and high policies have the high tariff (10%) plus the middle technology and the high technology assumptions, respectively.

Even the LoPol improvement has a substantial impact on emissions. Looking at 2050 emissions, introducing the club lowers emissions from61 $GtCO_2/yr$ to 36 $GtCO_2/yr$. These decline to 9 $GtCO_2/yr$ with the middle variant and -8 $GtCO_2/yr$ for the high variant in 2050. In other words, with a maximal effort to improve non-carbon technologies along with strong incentives to join the club, zero emissions are feasible by mid-21st-century.

Another question is the relative power of decarbonization and decrease in the cost of the backstop technology. Table 2 shows the impact on 2050 emissions of policies, starting from no policy, to four technological assumptions in a strong club. Both rapid decarbonization and a rapid improvement in the backstop technology improve on a strong club, although the backstop decline of 4% per year is slightly more powerful than more rapid decarbonization by 2% per year.

Policy Scenario	Emissions, 2050 (GtCO2/yr)
No Policy	60.6
Strong Club, Base Technologies	27.6
Strong Club, Rapid Decarbonization	8.6
Strong Club, Rapid Backstop Decline	2.4
Strong Club, Both	-8.0

Table 2. Interaction technological policies and the climate club

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 non-participants. Conversely, a large club that covers most countries will have maximal power to induce countries to participate.

To test the impact of club size, we examined the supportable emissions for club size from 0.01% to 99.9% of world trade. The results are shown in Figure 3 for 2050 emissions (using base parameters in Table 1). Not surprisingly, the larger the club, the lower the supportable emissions reductions. Additionally, the impact is non-linear, with a major reduction for even small club size. The non-linearity is shown in the analytical section above in equations (5) through (9).

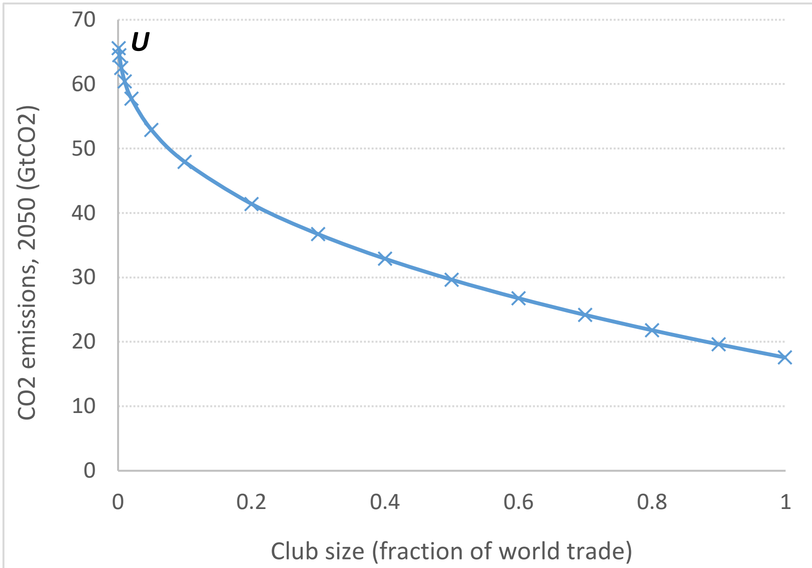

Figure 3. Sustainable emissions in 2050 for different club sizes

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The strong incentive of even small clubs is an encouraging feature, suggesting that a small group of countries with a modest fraction of world trade and emissions can start the process. This point is indeed the opposite of the current climate negotiations in the Conference 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 up at point *U* in Figure 3.

III. Effects of country heterogeneity in the TRICE model

The modeling of the TDICE model just described assumes identical countries. In reality, countries have different structures and therefore different benefits and costs, which would result in different supportable policies. A rough idea of the differences can be obtained by examining the key parameters for major regions. This model examines the behavior with 15 regions and is called the TRICE model.

What parameters are important to include in a regional model? The analytical model showed that the supportable policies will depend upon four parameters that differ across countries. These are openness, the welfare loss per unit tariff, the emissions-output ratio, the growth of total factor productivity, and the cost of the backstop technology. The dynamic model uses the same regional structure as the 2015 C-DICE model, with 15 regions (Brazil, Canada, China, EU, Eurasia, India, Japan, Latin American, Mideast, Russia, South Africa, Southeast Asia, Sub-Saharan Africa, US, and rest of world). The major parameters for each region are estimated from current data as described in the appendix.

The regional models differ for the parameters described in the last paragraph (GDP, cost of backstop technology, openness, tariff vulnerabilities, abatement cost, emissions, TFP growth, decarbonization rate, etc.). However, they have identical structures for several parameters such as population growth, rate of decline of TFP growth and decarbonization, and (obviously) the global climate model. The varying parameters are contained in Appendix Table A-1.

The results for the regional model are close but not identical to those for the aggregate model. For output, the initial levels are virtually exactly the same for the aggregated and regional versions. The growth rates over the 2015-60 period are 2.79%/year and 2.92%/year, respectively.

Figure 4 shows the results of the calculations for CO_2 emissions for four policy/technological assumptions for the aggregated and the regional models. Emissions for the regional version grow between 0.2%/year and 0.4%/year more rapidly that in the aggregated version.

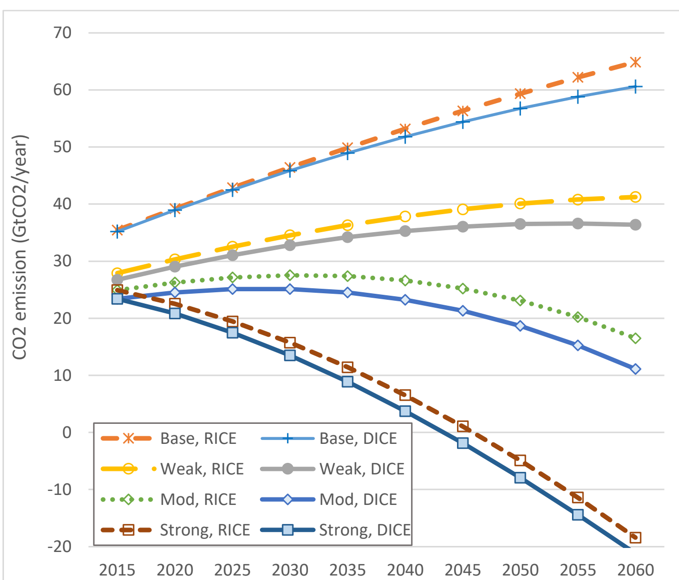

Figure 4. Effect of country heterogeneity on emissions for alternative assumptions

The figure shows calculations of supportable policies the aggregate (DICE) and regional (RICE) models. These are the same policy assumptions as in Figure 2.

Regional carbon prices

A first important question that is addressed when allowing for country heterogeneity is the difference in supportable price across region. Table 3 shows supportable carbon prices by region for the moderate climate policy. The calculations indicate that China and Russia have very low supportable carbon prices, in the order of \$80/tCO_2 in 2020. By contrast, Sub-Saharan Africa and Eurasia have high supportable prices, over \$200/tCO_2 in 2020. The differences are primarily due to the emissions-output ratio and estimates of the cost of the backstop technology. Note that they do not depend at all on estimates of damages.

Region	2015	2020	2050
World	139	148	221
Russia	68	72	97
Safrica	73	76	90
China	77	86	168
Brazil	91	91	85
EU	96	103	162
US	104	110	149
Canada	112	116	144
India	118	126	187
Japan	126	133	180
Mideast	138	141	159
SEAsia	161	173	256
LatAm	165	173	235
Eurasia	190	200	271
ROW	267	281	380
SSA	285	305	452
Wt average	101	109	170

Table 3. Supportable target carbon prices by region, moderate climate policies

Carbon price Laffer curve

Perhaps the most revealing result is the "carbon price Laffer curve," shown in Figure 5. This shows the relationship between the target carbon price and total emissions reductions (using 2050 as an example). Here is the point: At a zero carbon price, there are no emissions reductions. As the target carbon price rises, all participating regions reduce emissions as a function of the carbon price. However, when the target carbon price passes a country's supportable carbon price, the country drops out of the club, and the country's emissions go to the non-cooperative level. When the target price gets extremely high, there are no participants and therefore no emissions reductions.

Figure 5 shows how the impact of participation on emissions reductions using the regional model for three different penalty tariffs (0%, 5%, and 10%). Not surprising is that at 0% tariff the reductions and supportable carbon prices are extremely low and basically reflect the level of the non-cooperative policy. Additionally, the supportable prices rise with the penalty tariff.

The interesting result is the shape of the carbon-price Laffer curve. The peak emissions reduction comes at \$100/tCO_2 for the 5% tariff and \$160/ton for the 10% tariff (again, for the year 2050). The peak of the Laffer curve comes at a point that is close to the weighted average target price for 2050 of \$170/tCO_2, as seen in Table 3.

As a final point, note that an international agreement on a climate club will need to respect the differing interests of regions. For example, it might be that the US represents the key player and designs a club that is at its supportable carbon price. The price would be close to the average price shown in Table 3. A similar observation would apply to China. The 2050 prices would be \$149 or \$168 per ton CO_2 for the US and China. An alternative would be to choose the price that would maximize emissions reductions according to the carbon-price Laffer curve, which would be about \$160/tCO_2 in 2050.

There might be arguments here about the best choice of a target carbon price. But the central point is that any of these would be far above the current global policy, which has an effective carbon price of around \$5/tCO_2. Even a fractious and rowdy club would be superior to the current policy under the Paris Accord of national policies, nationally determined, and without any enforcement mechanism – clubs of one.

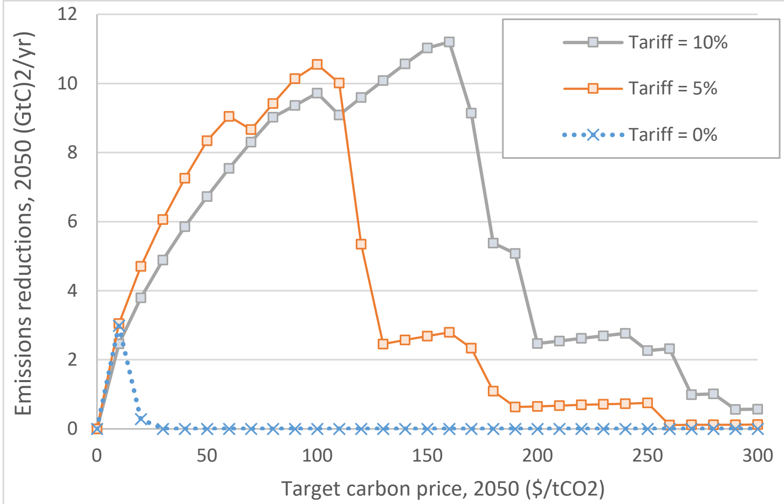

Figure 5. Emissions reductions at different target carbon prices for three different penalty tariffs, 2050

The sharp asymmetry of the curve arises for reasons unrelated to the structure of the club and is illustrated in Figure 6, which shows the curve for both the aggregated and regional models. Note that the curve has a sharp discontinuity for the aggregated model, where the break occurs at the (single) supportable price for the (one region) global model. Since the regional model has multiple supportable prices, the breaks will be smoothed out when aggregating the different regions.

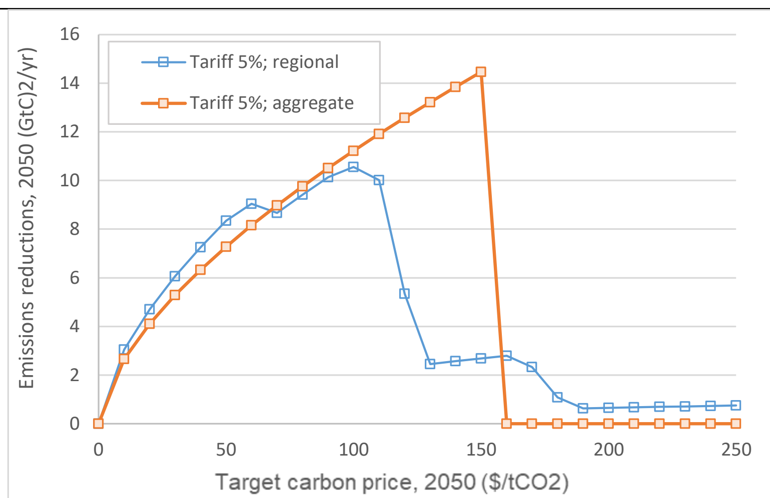

Figure 6. Emission reductions for aggregated and regional models.

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Appendix on multi-region assumptions

The multi-region TRICE model is a marriage of the earlier C-DICE model and the TDICE model described above. The TRICE model has 15 regions run in parallel but with different parameters as described below. The global averages are then the sum or the weighted averages of the 15 regions. The estimates have only an extremely small dependence on global variables (such as those determined by global climate change), so the errors of running independently are trivially small. The GAMS code is contained in the file Sources-Nordhaus-DynamicClub-091919.docx.

The empirical structure of the TRICE model is similar to earlier versions of the RICE model (Nordhaus-Yang 1996, Nordhaus 2010). It uses the same structure as the TDICE model with region-specific parameters as follows:

- The initial cost of the backstop technology varies by region according to the assumptions in the 2015 C-DICE model.
- The initial openness parameter is based on data from the 2015 C-DICE model and uses openness from 2011.
- The welfare parameter is based on data from the 2015 C-DICE model and uses results from Ossa (2015) and trade data from 2011.
- The value of the CO_2-GDP ratio (sigma) is determined from output data from the IMF, *World Economic Outlook* database, with CO_2 emissions from the EU (EDGAR), with the latest available data from 2017.
- Productivity growth by region uses output and population from IMF, *World Economic Outlook* database and take the initial growth rate at the average for the 2000-2018 period.
- The rate of decarbonization uses data from the IMF and EDGAR for the period 1980-2017.

All other parameters are identical for the TDICE and TRICE models.

The runs using the parameters above produced slight differences between the TRICE and TDICE versions. The parameters for TFP growth and decarbonization were adjusted slightly for China, India, the Mideast, and Southeast Asia to harmonize the aggregate and regional models. Table A-1 shows the adjustments to harmonize the two models. The "original" are the estimates constructed from the data as described above and the "adjusted" are the estimates after harmonization.

	Initial growth TFP		Initial rate of decarbonization	
Region	Original	Adusted	Original	Adusted
China	3.4%	2.5%	-0.5%	-0.6%
India	2.4%	2.0%	-0.1%	-0.3%
Mideast			0.2%	0.0%
SEAsia			-0.2%	-0.3%

Table A-1. Adjustments of parameters for regional model to harmonize with DICE-2016R3 in % per year for 2015-2020.