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Energy and the Global Economy

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Abstract. This article describes the contribution economists can make in uncovering energy choices capable of reducing carbon emissions on a global scale. All production and consumption activities involve the use of energy, and economists possess theoretical and analytic frameworks relating production and consumption in individual economies with international trade among them. Current challenges include deepening collaboration with physical scientists and engineers by according primacy to the formulation of scenarios and to the representation of physical stocks and flows of resources as factor inputs. Energy scenarios are discussed in terms of technological options, distinguishing those options that are already known but not yet widely applied from ones that still require research breakthroughs. Scenarios about household lifestyles and consumption in the areas of diet, housing and mobility are also discussed, distinguishing those that could already be initiated by households from those that would require changes in the built environment. Models and databases of the global economy have existed since the 1970s, and one was first used to analyze energy scenarios in the early 1990s based on the recommendations of the Brundtland Report of 1987. Relevant areas of progress since that time are described both in modeling the global economy and in compiling a global economic and environmental database. The paper concludes with a few examples of recent applications of a particular global economic model to analyzing energy scenarios to demonstrate both the progress that has been made and the nature of some of the challenges still to be faced.

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1. Introduction

The major societal concern of the 21st century is the destabilization of the climate system due to the atmospheric buildup of greenhouse gases. Emissions of these gases are linked to human choices throughout the world in the use of energy for production and consumption. The choices include the mix of fuels, the technologies by which they are extracted, transformed and distributed as energy services, and the amount of demand for energy services for different purposes.

Economists have little to contribute to estimating the extent of geologic reserves of energy resources, the relations between gaseous emissions and changes in their atmospheric concentrations, or the impact of atmospheric composition on the climate system. However, economists are the experts in the relations between global economic activities and the use of energy and, to some extent, about the possible feedback of climate change on the economic system. These relations are mediated by people's lifestyles and consumption patterns, whether in affluence or poverty, and the technological options embodied in stocks of capital. In addition, economists can contribute a global economic framework for analyzing the economic and environmental impacts of substantial changes in the economic activities involving the use of energy. They have only recently begun intensive collaboration with engineers and other experts in technology to assure that their representations of the technological options are concrete and realistic and not simply symbolic.

With globalization, the world economy operates more than ever like a single economic unit. Corporations scour the planet for the most advantageous sources of natural resources and human talent, and they expand production and achieve economies of scale by crossing borders in distributing their outputs. These advantages are translated into economic surpluses, part of which comes into the purses of employed workers and their households to increase the demand for goods and services that fuel the further expansion of the global economy. In our times the global economy needs to be viewed as a spatial unit of economic analysis that cuts across the familiar distinctions of the macro, meso and micro levels. The ways in which consumption, production and trade are carried out in the world economy determine the global demand for energy. Over the course of the 21st century there will be population growth, changes in average lifestyles especially in the rapidly developing economies, and new departures regarding energy sources and the technologies for exploiting them. Analysis of the operations of the global economy can help us understand what might be feasible ways to provide different quantities of energy without emitting carbon, and the economic requirements and implications of different energy options.

This paper argues for the primacy of formulating the questions that need to be addressed. Section 2 identifies the main components of energy scenarios and identifies, in the recent physical science literature, options for future energy sources that can be used to build alternative scenarios. The global economic framework for the analysis is described in terms of economic theory and models in Section 3, with an emphasis on the conceptual role of factors of production. Section 4 describes a data compilation project in progress and the kinds of challenges it faces. The final section provides a few examples of applications to illustrate what has already been done and points toward more ambitious research challenges in formulating and analyzing energy scenarios.

2. Energy Scenarios

2.1. Technology Assumptions

While technological innovations in general and as applied to energy in particular are the domain of engineers and applied physical scientists, there is also a substantial economic literature on this subject. But the question that concerns us here has barely been addressed: can familiar technologies assure global climate stability and if not what other technological options could achieve that goal? It is only with a model that can represent one technology as distinct from another, captures major interdependencies among economic activities, and scales up to the level of the world economy that one can hope to answer this question. But first it is necessary to identify the specific technologies in question.

A pair of starkly contrasting papers on this subject was published in *Science* in 2002 and 2004. In the first, Hoffert and colleagues argued that the targets for global carbon emissions assumed in most scientific and also public discussions (following the reports of the International Panel on Climate Change (IPCC)) cannot stabilize the climate "because much greater emission reductions will be needed, and we lack the technology to make them" (Hoffert et al., 2002, p. 981). They claim that stabilization requires achieving steady-state atmospheric carbon concentrations of no more than 550 ppm and that this outcome is sure to require emission-free power. The authors evaluate the potential contributions of a portfolio of "promising" approaches including: several sources of improved energy efficiency; decarbonization and effective sequestration of the carbon at the enormous rates of the latter that will be required; renewables, recognizing that land and other factor inputs can be limiting at the required scale; fission and fusion, which still require "aggressive" research and resolution of problems surrounding wastes and proliferation; and "risky" efforts of geoengineering, such as shadowing the earth by objects in space. The authors argue that these are the most promising options, all are in need of substantial, targeted, persistent R&D efforts to test their feasibility, and many are sure to fail this test.

In a rebuttal of this position, Pacala and Socolow argued that the earth's climate can be stabilized over the next 50 years at atmospheric carbon concentrations of 500 ppm. This target would be achieved by limiting emissions to today's rate of 7 billion tons of CO_2 per year using only "current technologies" (Pacala and Socolow, 2004, p. 968). Their business-as-usual benchmark scenario establishes a baseline emission projection of 14 billion tons of carbon per year by 2050, so a reduction of 7 billions tons relative to the benchmark is required. The authors describe 15 options and claim that each of them could be progressively scaled up to reduce emissions by at least 1 billion tons a year. The options are: more efficient vehicles, buildings, and baseload coal plants; reduced use of vehicles; gas baseload power in place of coal baseload power; capture of CO_2 at baseload power plants, H_2 plants, and coal-to-synfuel plants with geological storage for the carbon captured; nuclear or wind power substituting for coal power; wind H_2 in fuel-cell cars substituting for gasoline in hybrid cars; biomass fuel substituting for fossil fuel; reduced deforestation accompanied by reforestation; and the practice of conservation tillage (Pacala and Socolow, 2004, p. 970).

Leaving aside the apparent overlap between the two lists, it would be foolhardy to start by analyzing the impacts of the technologies discussed by Hoffert et al. since by definition their attributes are not known. By contrast, it should be possible to develop scenarios describing each one of the 15 options described by Pacala and Socolow in terms of their physical attributes and likely costs. Representing each option makes different demands on a model's structure and data requirements. Analyzing their joint implications using a model of the world economy would make it possible to capture two critical and related characteristics that cannot otherwise be quantified: a) the scale of change in the global economic system and the associated factor inputs, taking account of b) the interactions, especially at this non-incremental scale of operation, among the options themselves and between them and other vital functions of the global economy, starting with the provision of food, water, and shelter. The competition for land and fresh water between biofuels and food products is one evident example of such interactions.

2.2. Consumption Assumptions

Aside from technological options, discussed in the last section, the choices made by households are the other major determinant of carbon emissions. Household options start with decisions about fertility and extend to consumption patterns and requirements for mobility. These choices have received far less scientific scrutiny than technological options for several reasons. One obvious reason is that climate change research was initiated in the community of physical scientists, who only progressively came to acknowledge the decisive role of household decisions. It is also true that the general public and policy makers in turn would prefer that the problem be solved in ways that do not require changes in lifestyles, since the latter are generally interpreted to require giving up accustomed comforts in the rich countries and aspirations for a better material standard of living in poor countries. Those citizens who are motivated to make changes anyway are constrained by existing institutions and infrastructure, such as zoning practices and the physical layout of cities and towns. If envisaging a new energy system is daunting, changing the built environment of buildings, roads, parking lots, the network of gas stations, and other structures is even more so.

Nonetheless, social scientists have begun to investigate the prospects for changes in consumption patterns in three main areas: diet, housing, and mobility. As in the case of technological options, one can envisage two kinds of scenarios about changes in these areas. Some changes could be realized without major physical reconfigurations of public and private space; examples are buying food on the way home from work to reduce the number of car trips or turning down the thermostat by a few degrees. Much greater disruptions would be experienced if people substantially reduced their intake of animal products, and even greater ones if they abandoned suburban locations for a new vision of urban-density living.

As fuels from biomass get increasing attention from corporations, scientists, and the public, it becomes evident that household diets are intimately connected to climate change and to future prospects for the energy system. Scaling up the production of ethanol will compete directly with food production for agricultural resources. Of course, diets based on plant products would place lower demands on factor inputs, especially land, water, and energy per food calorie delivered, than diets based on animal products. Local provisioning requires less energy for refrigeration and transportation than a globalized food system. These attributes of household food choices are readily incorporated in alternative scenarios and their implications have begun to be studied, in particular by industrial ecologists (Duchin, 2005a). These kinds of changes in lifestyles do not require radical changes in household behavior. They could be considered in the category of practical options, like the technological options discussed by Pacala and Socolow.

The technology scenarios described earlier do not entirely ignore lifestyle changes. Interestingly, both examples center on cars. In their only mention of household options, Hoffert et al. (2002, p. 982) acknowledge that "Lifestyles also affect emissions" in a revealing discussion about efficiency improvements from more fuel-efficient cars. They point out that US consumers prefer SUVs to smaller cars and take that preference as inviolable, finding substantial improvement in SUV efficiency more likely than changes in car-related behaviors.

Of their fifteen options for reducing carbon emissions by at least one billion tons a year, Pacala and Socolow include exactly one that requires a decision on the part of households: reduced reliance on cars (p. 969). Here the proposition is to reduce the annual miles driven by the average car (of the two billion cars, or four times as many as today, assumed to be on the world's roads in 2054) from 10,000 to 5,000. Unfortunately, the paper does not discuss how this outcome could be achieved without substantial investment in public transportation and changes in living arrangements.

Formulating scenarios about changes in housing and personal mobility is far more difficult than changes in diet; the former are radical changes like the technological options described by Hoffert *et al*. Incremental changes are of course possible and should not be ignored: smaller living spaces, driving less, turning down the thermostat, using air conditioning more sparingly, buying more energy efficient appliances. However, the systemic change comes in replacing suburban by urban densities with mixed use for residential, commercial, and public purposes and some combination of expanded transport in common and reduced personal mobility. Understanding what this kind of scenario might look like, and how people might come to choose – or even accept – it, requires an intensive, interdisciplinary research program. Some work has been done along these lines, for example by Hertwich *et al.* (2004), but there is not yet nearly enough understanding of the housing and mobility options, and the interaction between them, to construct scenarios.

2.3. Analyzing Global Energy Scenarios

Duchin and Lange published the first study to use an input-output model of the world economy to evaluate the potential for reducing carbon and other emissions associated with the use of fossil fuels (Duchin and Lange, 1994). The study was undertaken in preparation for the Earth Summit in Rio de Janeiro in 1992. It set out to evaluate the recommendations of the Brundtland Report (World Commission on Environment and Development, 1987), the pioneering document that popularized the concept of sustainable development and argued for common goals and multilateral cooperation in achieving it. The objectives of the Brundtland Report were to substantially raise the material standards of living in developing countries, achieve at least modest rates of increase in the rich countries (for a nearly 3% annual rate of growth of real GDP globally), and at the same time greatly reduce pressures on the environment with a particular emphasis on lowering energy use and carbon emissions. The Report argued that these objectives could be achieved by means of a number of changes in technologies and lifestyles that were within grasp. The major problem foreseen was not the inadequacy of known remedies, but a shortage of capital for investing in the developing countries in the cleaner, more efficient technologies already available in the industrialized countries.

Duchin and Lange started from an existing input-output model and database of the world economy (Leontief, Carter and Petri, 1977; discussed below) and extended both model and database to evaluate the plausibility of the Brundtland Report's conclusions. Optimistic assumptions were made about energy savings with technologies used in: electric power generation, industrial energy conservation, the construction industry, the production of cement, pulp and paper, and chemicals. Assumptions were also made about household energy conservation and reduced use of more fuel-efficient cars. It was also assumed that the investment flows would be forthcoming to allow the rapid incorporation of these technologies in the developing countries. The authors compared the outcomes against a business-as-usual benchmark scenario and also tested the hypothesis that these measures would prevent carbon (and other) emissions from rising over the period between 1980 and 2020. While the assumptions attributed to the Brundtland Report resulted in substantial improvements in energy efficiency and in emissions relative to the benchmark scenario, CO_2 emissions rose in billions of tons from 4.7 in 1980 and 5.6 in 1990 to 6.8 in 2000, 7.7 in 2010, and 9.0 in 2020, with the richest economies accounting for 55% of total emissions in 1980 but only 30% by 2010. Clearly more drastic measures would need to be taken in order to stabilize carbon emissions.

In the years since the study by Duchin and Lange, many changes have taken place. In large part due to the influence of the Brundtland Report, the concept of sustainable development is well established as an objective. Today there is no disputing the strategic importance of focusing scenario attention on energy and carbon emissions, although the emphasis for many analysts has shifted over the past two decades from simply reducing the quantity of energy use to actually removing carbon from the energy system, a clear recognition that the assumptions of the Brundtland Report were too optimistic. Much more experience has been accumulated in the formulation of scenarios and scenario analysis. The collaboration of engineers and physical scientists, notably industrial ecologists, with economists is now intensive and sufficiently mature that one can hope to represent concrete detail about actual alternative technologies in scenarios. Several world input-output databases exist, and a database of unprecedented scope and detail, which will be documented and in the public domain, is being compiled. A number of models of the world of varying characteristics are in use and would rely on this input-output database as a shared resource, marking a high point for collaboration. There can be no more vital hypothesis to put to the test with these resources than a conjecture like that of Pacala and Socolow that the climate problem can be solved over the next fifty years with technologies that are already known and demonstrated and lifestyle changes that do not require reconfiguring the built environment.

Like the recommendations of the Brundtland Report, this last proposition tells a hopeful story. How realistic this story is remains to be seen. To test it, numerous scenario components need to be developed, one for each option, and the assumptions for each one quantified. The development of each scenario is itself a demanding research task. Technological assumptions will need to be combined with a parallel effort to produce a narrative and quantitative assumptions about population growth and changes in consumption behavior.

One possibility is that some combination of these technology and lifestyle scenario components can keep annual CO_2 emissions in the neighborhood of seven billion tons while satisfying assumptions about growth in population and improvements in well-being, at least for specific economies. However, if analysis leads to the conclusion that these options even in combination cannot do the job, then more radical changes need to be considered. These would focus on deep changes in consumption and lifestyles, on specific development strategies for China and other countries, and on far more challenging technological options, such as those described by Hoffert *et al.*

3. A Global Economic Framework

3.1. Modeling Challenges

The equations of an economic model represent presumed relationships among key economic variables with the strengths of relationships reflected in the values of parameters. With a model, it is possible to address questions about the impacts of hypothetical changes in certain variables on other variables, based on the assumptions that the equations do not change and that parameters change if at all in predictable ways. The scenario determines the variables and relationships that need to be included in the model and specifies values for certain variables and parameters. Results include changes in such variables as output, factor use, trade flows, factor incomes and prices. The results depend, of course, on the quality of the scenario formulation, the theoretical assumptions comprising the model, the adequacy of the data – and how well the three components fit together. Economists are skilled modelers, but mainly experienced with models of a single economy. They also have experience with multiregional modeling of sub-national regions, which has produced methods for quantifying regional interdependence. The pioneers in multiregional models of the world economy are Wassily Leontief (Leontief, Carter, and Petri, 1977) and Lawrence Klein (1985), whose relevant research in collaboration with colleagues started in the 1970s. The feature of a model of the world economy that decisively distinguishes it from other economic models is its reliance on an explicit theory of international trade to determine the production, imports and exports of each country, or regional grouping of countries.

A nation's comparative advantage is determined by an ensemble of attributes jointly determining its cost structures relative to those of potential trade partners. These attributes are: its factor endowments and their pre-trade prices, its consumption requirements, and the productivity of its technologies. The basic logic is that the relatively lowest-cost trade partner will produce a particular good until it runs into a factor constraint, at which point the next relatively lowest-cost partner will enter into production, and so on until world demand for the good is satisfied. Thus the representation of international trade requires two features that are absent in one-country models. First, individual factors of production that may turn out to be scarce in individual regions need to be represented conceptually as both factor endowments and inputs to production, that is, stocks and flows. It is important to recognize that, in a world economy characterized by extensive trade, a region's factor scarcities and scarcity rents respond to global demand, not just domestic demand, and can be determined only simultaneously with those of other regions. Thus the fundamental economic role of factors can be represented only in a global framework. Second, these resource stocks (or endowments) need to be measured in physical units, not only in money values, since they are used to determine when resource availability has been exhausted. In addition, of course, it is the physical quantities and attributes of resources that determine greenhouse gas emissions and other environmental discharges. Representing the limited availability of factors is crucial for a model of the world economy. See (Giljum *et al.* for a rare acknowledgment of this fact.)

Until recently no models of the world economy made direct comparisons of cost structures in different regions, nor did they include measures, let alone physical measures, of factor endowments. Instead of determining trade flows based on comparative advantage, most models still employ region-specific trade parameters that represent the ratio of imports of each good to its total domestic availability (called import elasticities in some models) and the share of the region's exports of each good to total world exports. Changes in these parameters are specified exogenously as part of a scenario. When trade flows are based on a direct comparison of cost structures, by contrast, trade flows are endogenous with no need of trade parameters.

Evaluating comparative advantage thus requires a new conceptual model that is less familiar. As is the case in other areas of scientific modeling, more reliance on economic theory takes the place of a representation of relationships dependent on exogenous parameters, which inevitably depend on subjective judgments. It also increases the transparency of the model, by clearly revealing the consistent logic underlying results.

The World Trade Model (Duchin, 2005b) is an input-output model of the global economy that introduces into the model of Leontief, Carter and Petri (1977) the determination of flows and prices of traded goods and services based on the theory of comparative advantage. This new model has successfully generalized the evaluation of comparative advantages, for the first time, to m regions, n sectors, and k factors. It is intended for implementation at a moderate level of detail, meaning dozens of regions, dozens or hundreds of sectors, and dozens of factors of production. The model is conceptually simple, consisting of only two basic (matrix) equations: one assures that production in all regions combined satisfies total world demand and the other, that each region's factor endowments constrain the amount of production that can take place in that region. Cost structures in all potential trading partners are compared directly, just like in textbook explanations of comparative advantage, except that solutions in the textbooks are limited to 2 regions, 2 goods, and generally a single factor. This representation will no doubt be incorporated into other world models, although one inconvenience should be noted: it will be more demanding to calibrate calculated trade flows to actual data for past time periods than in models where the analyst can adjust trade parameters one at a time.

In addition to its use for empirical analysis, Duchin's model has a well-defined conceptual structure allowing general theorems and propositions to be proved. The significance of this fact is that, as logical deductions, the theorems are independent of the numerical values of the data. In the case of the World Trade Model, the proofs of the theorems show (simplifying somewhat) that trading according to comparative advantage leads to a fall in world prices, and new world prices are such that each and every trading region experiences an improvement in its terms of trade. (This is not to say that all regions benefit equally, or even that all regions benefit unambiguously, as some may experience balance of trade deficits.) The World Trade Model (WTM) is capable of determining bilateral trade patterns by extending the logic of the cost comparisons to explicitly include the cost of transporting imports. In this case the different modes for the inter-regional transport of goods are included as industries, with their output measured in units of ton-kilometers transported, and the distances among regions and relevant product characteristics (such as tons per average unit of a good) must be given exogenously (Strømman and Duchin 2006).

A main feature of the WTM is the importance it accords to measuring resources and other factor inputs in physical units. Some goods and services are also measured in physical units, like tons of oil equivalent for fuels or ton-kilometers carried for transportation services. The data required for representing technologies in physical units draws heavily on the methods used for the life cycle inventories that are customarily prepared by engineers. The model is a linear program with the primal solution in physical units and the dual solution in prices.

Two distinct requirements must be satisfied by a scenario to be analyzed with the model. It needs a narrative that specifies what questions are being asked, what assumptions are being made, and what will constitute answers to the questions. It also needs to structure the story so it can be translated into the variables and parameters of the model. In recent work, WTM scenarios have been formulated in order to test hypotheses, rather than asking “What if?” questions. Hypothesis testing has the advantage of producing an unambiguous answer: a hypothesis either will, or will not, have to be rejected. The answer to a “What if?” question, by contrast, is not well defined in that a multitude of numerical results are obtained, and the selection of which ones to report and which to omit is subjective (see Duchin and Steenge 2007 on scenario analysis). Some examples of questions, scenarios, and hypothesis testing are given in Section 4.

A number of world models are in use today. They differ in many assumptions about economic relationships, in particular the theoretical determinants of trade flows. Nonetheless, all make use of a world input-output database extended with environmental data.

3.2. A Global Economic and Environmental Database

Consumption and production activities in individual economies and exchanges among economies can be fully described for a given time period by a database that quantifies all the constituent flows of factors and goods and services. Input-output databases containing this kind of information exist for most individual economies, and efforts are underway in Europe and in Japan to extend them to cover the entire world economy. A great deal of progress has been made in quantifying environmental flows in the framework called the National Accounting Matrix including Environmental Accounts (or NAMEA). These accounts vary considerably among the countries that compile them but often include physical measures of several gaseous emissions as well as resource inputs (flows) of energy and water. They are compiled using the same industrial breakdown as the national input-output tables.

Unfortunately, stocks of land, fresh water, ores and fuels are not yet included in NAMEAs. Compiling resource stocks in physical units for use in economic models is a major new challenge that will require the development of new definitions and conventions and new kinds of data sources. Part of the challenge is that the physical amount of the effective factor endowment depends both on geology and on the unit price of the resource. Furthermore, the flow is limited not only by the size of the stock but also by technical and economic considerations limiting the rate of exploitation.

Several projects now in progress are designed to take some next steps. One sets out to compile a new world input-output database: this is the objective of the EXIOPOL project (an acronym covering externalities, input-output accounts, and policy analysis) (Markandya and Tukker 2007). EXIOPOL will deliver detailed input-output tables for each of the member countries of the European Union plus several regionally aggregated tables for the rest of the world, along with data on resource flows and stocks, emissions, and costs of externalities. The database will for the first time include quantitative estimates of endowments of selected resource factors and bounds on annual rates of extraction. Using the database, scenarios about energy and about agriculture will be analyzed using the World Trade Model and other models of the world economy.

4. Applications and Challenges

Several empirical analyses have been carried out using the World Trade Model. Climate change affects the economy directly through its impact on agricultural productivity. To study this feedback, Julia and Duchin (2007) investigated how anticipated changes in climate would affect yields relative to demand. They expressed the question in the form of 2 hypotheses: 1) Under climate change assumptions about yields, today's quantities of food and fiber could still be produced and 2) Under climate change assumptions about yields, the relative prices of agricultural products will not increase. Several qualities of cropland and pasture were represented as distinct factors of production, and data from geographic information systems were incorporated to describe the likely changes in yields of different qualities of land as temperatures, precipitation, and length of growing season change. The climate change scenarios (corresponding to predictions of the 3 major climate change models[1]) matched the data to the variables and parameters of the World Trade Model. The database included 12 world regions, 10 sectors, and 3 factors of production besides land. Based on this analysis, only the second hypothesis had to be rejected: the relative prices of agricultural products increased because climate change entailed a move to croplands of lower yields. This conclusion differs from those reported elsewhere in the literature using the same yield assumptions but different economic models (computable general equilibrium models): the latter conclude that agricultural prices will continue their historic declines under the influence of climate change. The relative transparency of the World Trade Model makes possible close scrutiny of the reasons for the results, and the geographic locations of the croplands in question are explicitly identified increasing confidence in the results. Still, even these results are too optimistic in that they reflect demand for agricultural products at today's global population figures. A next step is to formulate a scenario that incorporates assumptions about population growth and changes in diets in both rich and poor countries over the next several decades and introduces an industry producing ethanol for fuel.

Another study using the World Trade Model examined to what extent progressively tightened carbon constraints would impact the international division of labor or, to put it the other way around, to what extent changes in the division of labor could reduce carbon emissions (Strømman, Hertwich and Duchin, 2007). The model was run with two different objective functions, one minimizing factor use and the other minimizing carbon emissions. Minimal carbon emissions were realized essentially by shifting energy-intensive industries out of coal-dependent regions to regions using other fuels. Minimizing anthropogenic carbon emissions reduced the volume of international transport of goods (measured in ton-kilometers) by 40%, reducing total carbon emissions

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[1] The 3 major climate (or global circulation) models are those produced by: the Goddard Institute for Space Studies (GISS) of the US National Aeronautic and Space Administration, the General Fluid Dynamics Laboratory (GFDL) of the US National Oceanic and Atmospheric Administration, and the United Kingdom Meteorological Office (UKMO).

by about 5% compared to the economically optimal solution. Up to 2/3 of that carbon reduction could be achieved at an average cost of about $115 per ton of CO_2; for comparison, this carbon fee is at the high end of the IPCC estimates for the cost of reductions from more efficient personal transport. To achieve the remaining 1/3 of these potential carbon reductions, however, would involve even very steeply higher per-ton costs. These empirical results are suggestive of the limited extent to which a strategy of national self-sufficiency could contribute to carbon reductions. However, the analysis is still far too aggregated. More detailed scenarios will require considerably more regional and sectoral detail, such as that being developed for the EXIOPOL project, and the analysis also needs to allow for alternative technological options within each economy, drawing on the kinds of scenarios described in earlier sections.

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