From recursive-dynamic to forward-looking: The importance of allowing for intertemporal investment and net trade adjustments

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Abstract: Many CGE models analyzing the cost of climate policies are recursive dynamic in order to take into account much sectoral and regional detail. Introducing forward looking behavior might be preferable from a theoretical perspective because it allows agents to endogenously adjust intertemporal investment and trade decisions, however, this comes at computational cost. Here we present three versions of the same model (forward looking, recursive dynamic, and an intermediate case which only restricts intertemporal trade decisions) and compare outcomes for exemplary climate policies. Limiting intertemporal adjustments makes climate policy more costly. Preliminary results suggest that the intertemporal adjustments via trade are more important than adjustments via investment decisions if the baseline starts from a first best capital path, but that might depend on the type of policy to be implemented.

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Introduction

A large range of CGE models exist to assess economic impacts from climate policies. Modelers are faced with a trade-off on how to treat the dynamic aspects of the response: one the one hand, high sectoral and regional detail is desirable, but on the other hand, stricter adherence to economic theory and allowing for intertemporal optimization are favored. Allowing for intertemporal optimization of investment and consumption decisions increases however the computational burden because the model can no longer be easily split into smaller problems which can be solved faster and more reliably.

Models which analyze longer term pathways of climate policy and include intertemporal optimization usually do so at the cost of abstracting from higher spatial, sectoral or temporal resolution (e.g. models of the DICE/RICE family have only one economic sector, the REMIND and WITCH models have a more detailed energy representation but are limited to one overall macroeconomic sector). Solving forward-looking multi-regional CGE models "in a single shot" is inherently numerically difficult as future periods are discounted and hence small prices and large quantities cause both very small and very large numerical values to be solved for simultaneously, which can lead to scaling issues for the solvers to cope with.

Models with larger sectoral or regional detail (e.g. ENV-Linkages, EPPA, GEM-E3, Phoenix, DART) are usually ran in a recursive dynamic manner which determines investment decisions based on an exogenous rule (e.g. constant savings rates or savings rates which are adjusted according to the current periods' prices) and not based on impacts from a policy that only affects the future. While these models can provide more detailed answers how different sectors or regions are affected, agents are not allowed to adjust their investment and consumption decision in anticipation of the policy.

There are also models (e.g. iPETS) which are forward looking in terms of domestic capital but with limitations for international capital as there is an exogenous balance of payments constraint in each period. This is due to the solving algorithms applied in this class of models. Only one state variable is tracked (the capital stock) and adding another state variable (international financial capital) would be very difficult or impossible to add. This class of model can be solved iteratively by solving individual periods much like a recursive model and solving for the optimal capital stock path taking individual periods as given. This approach becomes however very complicated or infeasible if more than one state variable has to be tracked (e.g. net assets with the rest of the world and the capital stock).

From theoretical perspective, a forward looking model might be preferable to perform a clean welfare analysis which starts from a first best baseline. In the presence of other distortions such as taxes, a recursive model could theoretically lead to policy results in which a policy leads to a spurious welfare improvement because the exogenously prescribed investment behavior fits better to policy than to the baseline. In other words, the limitation of the agent's behavior to adjust its investment decisions in a recursive dynamic model is another distortion which can interact with other distortions in the model.

However, perfect foresight with complete information for long time periods is a strong assumption and could justify recursive models which are agnostic about future time periods (some models use signals such as investment prices that modify investment decisions, but only on current, not on future periods' indications).

A priori it is not clear how important the modelers' choices about forward looking behavior are and there is little comparison between forward-looking and recursive dynamic models. One exception is Babiker et al. (2009) who compare welfare and energy outcomes from climate policies under those two model classes. They conclude that energy sector outcomes are similar in both models but policy costs are smaller once intertemporal adjustment is allowed for. Policy costs are lower because agents can anticipate the shock and adjust investment and trade decisions prior to the actual shock. We here revisit this issues and focus on the role of intertemporal optimization and the importance it makes for exemplary climate policies. Using a multi-region, multi-sector CGE model, we build multiple model versions that allow for different degrees of intertemporal optimization. More specifically, the model can be transformed to resemble the three classes of models mentioned above:

- A perfect foresight model which allows agents to optimize over one budget constraint for the entire model horizon. For each region, a constraint specified net present value of a trade deficit over the entire model horizon. A region thus can use trade deficits or surpluses to adjust its investment and consumption decision in any particular year.
- A limited foresight model which allows endogenous investment decisions based on perfect information on the entire model horizon. In contrast to the perfect foresight model, we do not allow making use of international financial capital, i.e. a region cannot run trade deficit (that it would repay later in the model horizon) as a mean to borrow. This is implemented in the model via endogenous taxes/subsidies on trade flows which ensures that the balance of payments in each simulation year reaches a fixed, endogenous level.
- A recursive dynamic model with budget constraints for each model period. Investment cannot be adjusted based on expectations and is set to an exogenous savings rule. The scenario is implemented by an exogenous demand for investment in each period rather than leaving that decision to the representative agent in the respective region.

The model versions and policy scenarios are described in more detail in the next section and preliminary results are discussed afterwards.

Model Versions and Policy Scenarios

To analyze the importance of forward looking behavior and the consequences of not allowing for some or all factors of forward looking behavior, we use variants of the iPETS model (O'Neill et al., 2010; 2012). The iPETS model has historically been used for the analysis of emission trends under different demographic and urbanization trends, but has also participated in model comparison studies on climate policies. The iPETS model is based on GTAP 7 data (Narayanan and Walmsley, 2008) which represent a snapshot of the global economy in the year 2004. In each period, producers are minimizing unit costs by substituting the input shares subject to nested CES production functions and consumers maximize utility. For the consumption sectors, output from intermediate goods sectors is combined to 6 consumption goods (electricity, coal, other energy, food, transport, and other goods and services). The preferences to consume these goods change over time, mainly driven by demographic and income changes in income (O'Neill et al., 2010; 2012). The world is aggregated to 9 larger regions, which are linked to trade flows modeled using the Armington assumption. A list of sectors and regions can be found in the appendix. The nesting structure is documented in O'Neill et al. (2012).

The model is written in Fortran and its code is available online. The Fortran version of the model is solved by splitting the problem into single period problems and the intertemporal problem which is making a choice over consumption and investment all periods. The structure does not allow for optimizing over the balance of trade, instead a constant balance of trade in each period is assumed. For this analysis, we use a model version formulated in GAMS which solves the model “at one shot”, i.e. simultaneously solving all periods and the intertemporal model.

All model versions are calibrated to a common scenario (“middle of the road” or SSP2 scenario from the shared socioeconomic pathways, see appendix for details) with respect to GDP and energy use. The model horizon is 2100 and the time steps are 10 years, i.e. the years 2010, 2020 etc. are solved explicitly. The general economic structure with regard to sectors, base year data, and nesting remains constant over all policy scenarios.

The dynamic calibration of this model follows the strategy outlined in Balistreri (1997) and Babiker et al. (2009). First a steady state growth path is set up based on initial data. To reconcile investment, the capital stock, and rental payments to capital with reasonable returns on capital, a (implicit) tax on the capital rental is assumed (see Balistreri, 1997).

To produce a meaningful scenario, the steady state baseline is shocked with regard in order to match several target variables. These are either obtained from the GCAM interpretation of the SSP 2 (shared socioeconomic pathway) or own assumptions. The SSP 2 is a “middle of the road” scenario and information on GDP and energy use is used to create a baseline.

Starting from the steady state baseline, preferences are adjusted to reflect changes in demographics and income and energy prices are adjusted by adjusting the resource specific capital in the three extraction sectors (coal, gas, crude oil). Then, GDP is adjusted to match an exogenous target by adjusting labor productivity. As the forward looking model tends to project very high investment shares for some regions over the entire century adjustments to the rate of the tax on capital rental as well as investment productivity were made. This leads to a savings rate of roughly 20% at the end of the century. Energy use is adjusted to reflect use of all energy sources in all different regions based on data from the GCAM model. Energy calibration is carried out by adjusting input share parameters in the production function. This method shifts the calibration point along the isocost curve and follows Böhringer et al. (2009). Once the benchmark scenario is reached, all calibration parameters (labor productivity, input share parameters, resource specific capital) are held constant in the policy scenarios.

In this study, three model versions are constructed which differ in their treatment of investment and capital as well as their treatment of trade. The latter is adjusted when the model is prescribed a fixed balance of payments constraint and the agents cannot decide whether an alternative temporal schedule of trade surpluses or deficits might be preferable. The former is adjusted by restricting investment to an exogenous amount. The relevant changes in the different model versions are detailed below.

Forward looking model

In the forward looking model, the representative agents in each region face only one budget constraint which covers the entire model horizon. This includes the net present value of net trade. This allows regions to run a higher trade deficit in any given period, given that the rest of the world is willing to finance this and that it is repaid within the model horizon. With regard to investments, the agent is endowed with an initial capital stock to which the agent can add by investing. To avoid depleting the entire capital stock in the final simulation years, a terminal constraint is put in place to ensure that investment is growing at the same rate as consumption in the final period (Babiker et al., 2009).

Fixed balance of trade in each period

To limit the ability of the agent to decide on trade surpluses and deficits in each period, a constraint is added which holds the balance of trade constant in each time period. In the case of emission trading, the value of carbon permit trade is included in this constraint. The variable that is associated with this additional equation is an import tariff or an export subsidy on imports and exports, respectively. As the import tariff and the export subsidy are mirror values of the same rate, this instrument is not distorting when the balance of trade is zero. In this case, the government does not receive any gains from the trade restrictions. Per Walras law, one region has to be left out as its net trade with the rest of the world is already determined when all other regions face such a constraint.

Recursive dynamic model

The recursive dynamic model is branched off from the model with a fixed balance of trade in each period after calibration. In other words, the initial investment decisions to construct the baseline are optimal, but in the policy scenarios, the agent has to maintain the savings rate the of the baseline scenarios. While technically the model still only has a single budget constraint, the capital stock decisions are no longer endogenous as the investment demand and the resulting capital endowments in each period are now governed by a set of constraint. One constraint keeps track of the capital stock dynamics and the available capital stock in each period which another constraint is designed to keep the level of investment (or the savings rate) at a fixed rate. This is included in the budget equation of the agent so that there is a fixed investment demand in each period given the GDP in this period.

Policy shocks

We analyze to illustrative climate policy scenarios. Both scenarios are stylized in order to show the effects of different modeling assumptions rather than presenting realistic mitigation pathways such as outlined in the Paris Agreement. The nature of these scenarios is more academic and the results should be interpreted as such.

In the first policy scenario, only the EU is imposing a carbon tax of 25$/ton CO2 in 2020 which is increased to $100 in 2050. This scenario admittedly is highly stylized but is chosen to have a limited regional scope of policy and also to introduce more sudden changes around certain time periods (2020 and 2050) that require more sudden adjustments.

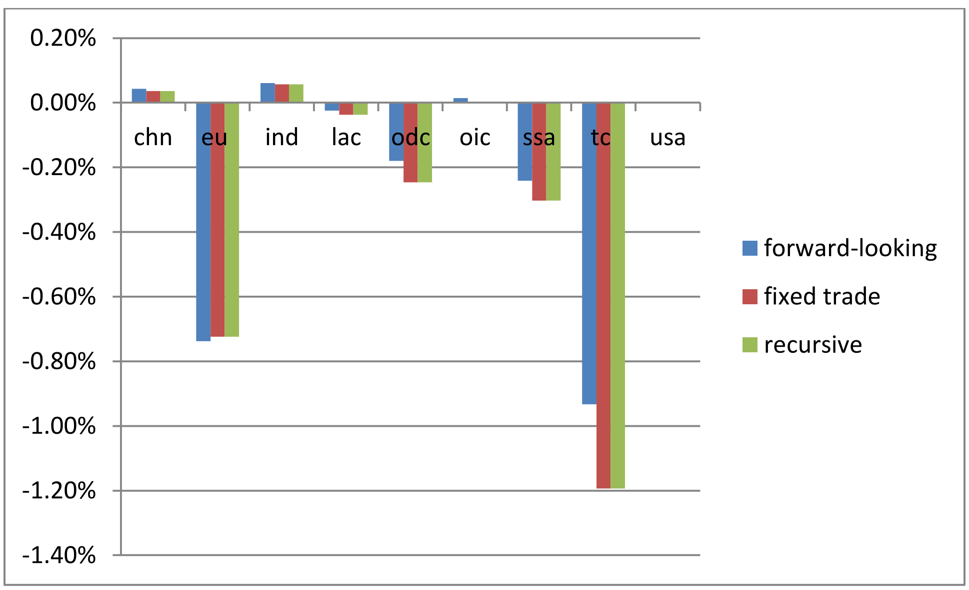
In the second policy scenario, a global climate policy is put in place and global emissions are restricted to roughly follow the emissions trajectory of RCP 4.5 (Thomson et al., 2011). Emissions peak in 2040 and radiative forcing is stabilized in 2100. Global emission trading is put in place and emission rights are allocated based on equal reduction rates compared to the region's emissions without policy. This climate policy scenario allows analyzing (intertemporal) trade effects from carbon trading.

(Preliminary) Findings

We first present intertemporal welfare impacts of the two climate policy scenarios. This already provides a good indication on the mechanisms that are at work. The measure of intertemporal welfare is the objective in the forward looking model and is calculated with an intertemporal elasticity of substitution of 2. The

Figure 1 presents the welfare consequences from a unilateral carbon tax in the EU in the three model versions. In all model versions, the EU is faced with a cost from the policy, but also energy exporters (most notably TC, and to some extend also SSA and ODC) suffer from this policy as the price for fossil fuels gets depressed. These countries cannot adjust intertemporal trade to sell their exports earlier at a higher profit when intertemporal trade adjustments are restricted. China and India have moderate welfare gains due to leakage effects and relocation of production to regions where emissions are not controlled.

Figure 1: Welfare effects in the unilateral tax scenario

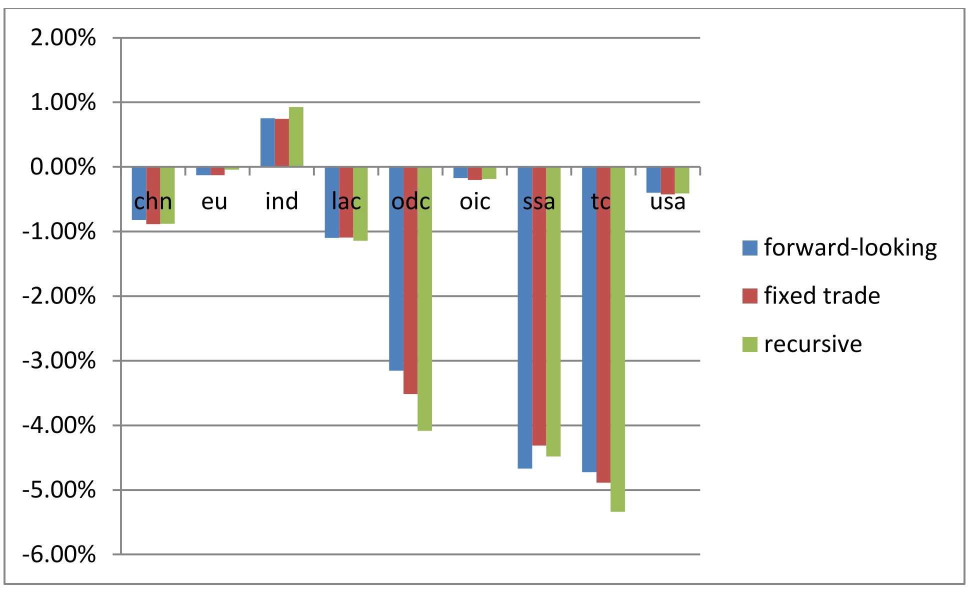


When comparing the effect of restricting intertemporal adjustments of trade ("fixed trade") and investments ("recursive" model), costs are higher globally because the agents are restricted in their adjustments to the policy. This holds true especially for those regions that benefit or suffer because of intertemporal trade responses. However, this is not true for all regions, most notably the EU is slightly better off under more restrictive settings. This is mainly due to the fact that energy exporters are limited in their response.

It is obvious that almost the entire different between the forward looking model and the recursive model is already present in the model that only resticts trade adjustments but still allows flexible choices about consumption and investment in each period. One reason why the decision about the capital pathway has very little influence might be because the policy does have relatively little impact on the other regions and all regions initially start from a first best baseline. If the policy does not bring the regions too far away from this, very little additional cost is induced by holding investment rates constant because the changes from the policy are not large enough to induce incentives for adjusting the capital dynamics.

Figure 2 shows the welfare effects from a global carbon policy with carbon trade, so welfare impacts include both the direct effects from mitigation action as well as more indirect effects from fossil fuel trade and trade in carbon permits. Again, global welfare costs are higher in the scenarios that restrict intertemporal adjustments of investment and trade. These effects are larger in regions that initially already suffer from higher costs due to domestic abatement costs as well as reductions from foreign demand for fossil fuels. There are however some exceptions (India, EU), where the forward looking model suggests a worse outcome despite offering more adjustment options.

Figure 2: Welfare effects in the global emissions trading scenario



With the regard to the importance of the two intertemporal adjustments, there is no clear result whether trade or investment constraints are more important in determining welfare changes. The trade effect in this policy scenario not only includes intertemporal decisions about trade in goods, but also in carbon permits. Restricting the balance of trade in each time period also affects how many carbon permits are traded internationally. The volume of trade in permits is following a different temporal pattern in the forward looking model and in the two models which restrict the balance of payment. With unrestricted trade permit trade the initial trade volume is lower, but when higher when carbon prices are more expensive. This leads to some intertemporal borrowing in mitigation action which is traded not only across countries but also across time. Depending on the marginal abatement costs, regions might thus do more abatement in periods where their abatement is low and less abatement when their abatement costs are high. There are however limitations to this behavior as this scenario did not allow for adjusting the temporal pattern of global abatement and emission levels in each period where exogenously specified.

Discussion and further steps

The welfare changes resulting from different models to analyze the same policy show are different (with the forward looking model yielding lower policy costs, as expected), yet, these differences are not very large. Qualitatively, regional cost distributions are also relatively similar in the different model versions and comparison with other sensitivity studies would suggest that these differences are in the range of other model uncertainties like parameter uncertainties. One reason for the relatively low importance of the different model choices might be the fact that not only policies where relatively stylized, but also related to other features of the scenario and model design.

The model has a very generic representation of capital, capital is freely mobile across sectors. This makes the choice of investment less important to a model in which capital is sector specific and investment decisions have more consequences. In these cases, perfect foresight might alter investment decisions more drastically compared to a recursive dynamic model.

Furthermore, the time steps in the model are currently set to 10 years. This means that a relatively large fraction of the capital stock gets depreciated from one explicitly modeled time period to the next. This reduces the importance of agent's decisions on consumption investment trade-offs. Moving the model to more time steps is relatively easy, yet adds computational burden as the problem to solve grows non-linearly with regard to the time periods considered.

The scenario baselines are very similar. For both models that include a fixed balance of trade, the baselines are identical and only the behavior to the policy shock is constrained to different degrees. This is desired to show the effect of policies starting from a first best baseline. With little deviation from this baseline, the policy shocks are not large enough to fundamentally change the agents' desire with regard to trade or to savings. Therefore, the policy cost increases from introducing limitations on the adjustments that the agent can make are relatively modest. However, when a modeler is faced with constructing a model from scratch and then constructing a baseline, the agents' optimal savings behavior might not be known. This might lead to drastically different behavior on savings and intertemporal trade. If the modeler thus creates a baseline scenario from a recursive model, this might then imply much larger differences in the policy costs than in these scenarios where the recursive model was branched off from a forward looking model with already some knowledge about how the agents would like to build their capital stock over time.

Appendix:

List of regions in the iPETS model

- CHN – China
- EU
- IND – India
- LAC – Latin America
- ODC – Other developing countries
- OIC – Other industrialized countries
- SSA – Sub-Saharan Africa
- TC – Transitioning countries
- USA

List of sectors in the iPETS model

- Intermediate Goods sectors
    - Coal
    - Gas
    - (Crude) Oil
    - Refined Oil
    - Electricity
    - Materials
- Final demand sectors
    - Government purchases
    - Investment good
    - Household electricity use
    - Household coal use
    - Household other energy use
    - Food
    - Transportation
    - Other consumption goods and services

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