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Summary

Computable general equilibrium (CGE) models are widely used to analyse macroeconomic and sectoral effects of climate policies. Developing new and improving existing carbon-free energy technologies will be crucial to limit the long-term economic costs of mitigation policies. Such technologies are largely embodied in capital goods; yet conventionally structured CGE models cannot capture capital-embodiment of sector-specific technologies. In this paper, we clarify the conceptual nature of the capital embodiment problem in multisector CGE models. Aggregating productive sectors and investment goods eliminates channels whereby specific technological changes are embodied in specific capital stocks. Nevertheless, capital-embodiment of sector-specific Hicks-neutral technical changes can be directly represented as investment-specific technical change (ISTC).

We consider a narrow but practically relevant application of these concepts in the context of long-term climate mitigation scenarios. Using a modified version of the Intertemporal Computable Equilibrium System model featuring sector-specific capital, we model change in solar and wind technologies alternatively as investment-specific or capital-augmenting. In this specific comparison, the alternate specifications give very similar results. However, the ISTC specification has no obvious practical disadvantages, is preferable in principle and results will differ in general from those using the conventional specification. The specification with ISTC would also extend naturally to model learning-by-doing in sector-specific technologies. This would greatly strengthen the dynamic relationship between investment and technical change.

Keywords: Climate Change Mitigation, Capital-Embodiment, Technological Change, CGE Models
JEL Classification: O33, O44, Q54, Q55, Q58

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Capital-embodied technologies in CGE models

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ITALY

Abstract

Computable general equilibrium (CGE) models are widely used to analyse macroeconomic and sectoral effects of climate policies. Developing new and improving existing carbon-free energy technologies will be crucial to limit the long-term economic costs of mitigation policies. Such technologies are largely embodied in capital goods; yet conventionally structured CGE models cannot capture capital-embodiment of sector-specific technologies. In this paper, we clarify the conceptual nature of the capital embodiment problem in multisector CGE models. Aggregating productive sectors and investment goods eliminates channels whereby specific technological changes are embodied in specific capital stocks. Nevertheless, capital-embodiment of sector-specific Hicks-neutral technical changes can be directly represented as investment-specific technical change (ISTC).

We consider a narrow but practically relevant application of these concepts in the context of long-term climate mitigation scenarios. Using a modified version of the Intertemporal Computable Equilibrium System model featuring sector-specific capital, we model change in solar and wind technologies alternatively as investment-specific or capital-augmenting. In this specific comparison, the alternate specifications give very similar results. However, the ISTC specification has no obvious practical disadvantages, is preferable in principle and results will differ in general from those using the conventional specification. The specification with ISTC would also extend naturally to model learning-by-doing in sector-specific technologies. This would greatly strengthen the dynamic relationship between investment and technical change.

Introduction

The Copenhagen Accord (UNFCCC, 2009) expresses a broad international consensus that actions should be taken to keep global warming below 2°C. Achieving this will require rapid and extensive development of and investment in low- and zero-carbon technologies over the next decades (Edenhofer et al., 2010; Luderer et al., 2012). Moreover, this must be achieved against a backdrop of population growth, demographic change, and economic development. Computable general equilibrium (CGE) models have been widely used to construct complex scenarios involving all of these factors and to analyse macroeconomic and sectoral effects of emissions pricing and other climate policies.

The great strength of CGE models is their ability to represent interactions between different sectors and regions of an economy in a framework that has strong foundations in microeconomic theory and simultaneously satisfies key macroeconomic constraints. This distinguishes them from macro-energy models, which provide more technologically detailed representations of energy supply (and in some cases, energy use) but abstract from many details of the production, trade and consumption of non-energy goods and services. Nevertheless, because a large majority of global greenhouse gas emissions are associated with energy supply and use, CGE models focused on this issue are frequently enhanced to distinguish key fossil and carbon-free technological alternatives.

Despite the attention of CGE modellers have given to energy supply and use and their recognition that technological progress is central to achieving climate policy goals, we argue that improvements in energy technologies are poorly represented in conventionally structured CGE models.[1] These models feature richly structured production functions with multiple intermediate goods. However, they do not allow for heterogeneity in capital goods. Yet many technologies, especially energy technologies are, to a significant extent, embodied in capital goods. In this context, treating capital goods as homogenous ignores complex and dynamic relationship between technological change in up-stream sectors and capital accumulation in down-stream sectors.

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[1] By 'conventionally structured', we refer to CGE models in which the overall modelling approach is the same for energy and non-energy sectors alike. This is in contrast to hybrid modelling approaches – also referred to as 'bottom-up/top-down' (Böhringer & Rutherford, 2008) – that may be seen as CGE analogues of macro-energy systems models.

In this paper, we analyse the problem of embodied technical change in multisector CGE models. The first contribution of this paper is to clarify the origins of technological embodiment in this framework. The extent to which embodied technical change arises endogenously in a CGE model depends crucially on the extent of disaggregation of capital goods producing sectors and of the capital goods themselves. In particular, the usual aggregate production function for investment goods in a multisector CGE model precludes capital-embodiment of sector-specific technologies. However, we argue that a practical alternative is to use the device of investment-specific technical change (Krusell, 1998) or ISTC to exogenously introduce sector-specific and capital-embodied technical change that is missed due to aggregation.

The second contribution of this paper is a numerical evaluation of the suggested modelling approach in a context that is relevant to climate policy modelling. We focus on modelling change in new energy technologies; specifically, solar and wind electricity generation. We compare the results of modelling technical changes in these sectors as being investment-specific with those of modelling them as being disembodied. Technologies are calibrated such that outputs in these sectors are the same in the baseline scenario. For this exercise, we develop a modified version of the ICES (Intertemporal Computable Equilibrium System) model. ICES is a recursive-dynamic multiregional general equilibrium model that has been developed to study economic impacts of climate change, as well as climate policies (Bosello, Nicholls, Richards, Roson, & Tol, 2012; Eboli, Parrado, & Roson, 2010). In the version of ICES used here, which we will denote ICES-K, we allow for sector-specific capital and investments and for sector-specific ISTC.

Sector-specific technical changes in CGE models

Technical change

Sector-specific technical changes in multisector CGE models are usually represented as improvements in the productivity of some or all inputs to a sector. Let the production $y_{j,t}$ of the representative firm in sector j be a function of inputs of capital $k_{j,t}$, labour $l_{j,t}$, and a vector of intermediate inputs $\mathbf{x}_{j,t}$:

$$y_{j,t} = a^{Y}_{j,t} f_j \left(\mathbf{a}^{\mathbf{X}}_{\mathbf{j,t}} \circ \mathbf{x}_{j,t}, a^{L}_{j,t} l_{j,t}, a^{K}_{j,t} k_{j,t} \right). \tag{1}$$

Increases in $a_{j,t}^{Y}$ describe Hicks-neutral technical progress while increases in $a_{j,t}^{L}$ describe Harrod-neutral technological progress.[2] Increases in $a_{j,t}^{K}$ describe disembodied capital-augmenting technical change, which we will refer to below as KATC. In the context of climate policy modelling, so-called autonomous energy efficiency improvement (AEEI) are modelled by increasing relevant elements of the vector $\mathbf{a}_{\mathbf{j,t}}^{\mathbf{X}}$. Finally, capital-augmenting technical progress is described by increases in $a_{j,t}^{K}$.

In this specification, each good is characterised only by its price. Changes in quantity and quality cannot be distinguished in this setup; still less changes in particular product qualities, such as energy efficiency. Neither then can we make a substantive distinction between process and product innovation. However, with multiple sectors, it is possible to model the impact of process or product innovations in up-stream sectors on costs in down-stream sectors. Improved technologies may be embodied in intermediate or capital goods used by downstream sectors; or equivalently in this framework, reduced up-stream costs may be passed down-stream. These relationships depend critically on the level of aggregation of sectors and goods in a CGE model.

In a multisector CGE model, there is usually one technology of production per sector plus one aggregate technology for producing capital goods. This is consistent with the structure of the supply and use or input-output tables (UN SNA, 2008) produced by national statistical agencies models. These tables describe the flow of intermediate goods between all sectors but do not link the supply of investment goods by sector to the demand for capital and hence net and gross investment of each sector. Only the aggregate demand for each investment good is identified. Thus while in principle, capital goods could be treated analogously to intermediate goods in a CGE model, doing so would pose severe data problems.[3] In addition, it would substantially increase the size and numerical complexity of the model.

In addition to the aggregate treatment of investment in standard CGE models, flows of technology between sectors may be obscured simply by the need to aggregate individual firms and goods into

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[2] Harrod-neutral technical change has a particular prominence in multisector CGE modelling because (unless the economy is Cobb-Douglas) it is the only form of technical change consistent with balanced growth.

[3] The KLEMS database (O'Mahony & Timmer, 2009) offers some limited possibilities to link sectors of supply and use via a classification of investment goods. For example, non-residential construction will be supplied predominantly by the construction sector.

sectors and commodities. In contexts such as climate change, one is concerned with quite specific sets of technologies. These may not be well resolved in terms of sectors and commodities as defined in standard datasets. For example, the Global Trade Analysis Project (GTAP) database underpins most global multiregional CGE models. In this database, one sector 'machinery and equipment nec' produces everything from wind turbines to boilers to electric motors. Another sector, 'motor vehicles and parts', produces conventional internal combustion engine, hybrid and electric vehicles.

Sectoral disaggregation offers a partial solution to the problem. For example, many CGE models developed for climate policy analysis distinguish between fossil-fuelled, nuclear and renewable electricity production. However, in this case as in many others, much of the technical change occurs not in the use of a technology but up-stream, in its production; especially in the production of various types of capital equipment. For example, wind power has become cheaper primarily because of improvements in turbine design and manufacture and only secondarily because of improvements in siting, operation and maintenance. To explicitly model these technology flows would require not only disaggregating the up-stream manufacturing sectors but also a disaggregated treatment of investment goods, as previously discussed.

In practice, it is inevitable that the down-stream effects in any given sector will be under- or over-estimated to some extent. In principle, these errors may be corrected by representing part of the technical change as occurring up-stream and the remainder as occurring down-stream. In the case of intermediate inputs, changes to the corresponding technology coefficients can correct for the difference between the predicted and modelled level of embodied technical change; that is, for the difference between the predicted and modelled relative input price. In the case of capital inputs, the problem is more complex. It is inappropriate to adjust the coefficients $a_{j,t}^{K}$, since the current upstream technology is embodied only in *newly* installed capital. The solution is to model missing capital-embodied technical change as being 'investment-specific'. That is, the technology coefficient $a_{j,t}^{Z}$ multiplies the input of the aggregate investment good to yield the effective gross addition to the capital stock of sector *j*:

$$k_{j,t+1} = \left(1 - \delta_{j,t}\right) k_{j,t} + a_{j,t}^{Z} z_{j,t} \,. \qquad (2)$$

This device of investment-specific technical change (ISTC) is borrowed from the macroeconomic literature (Greenwood, Hercowitz, & Krusell, 1997). It is a restrictive type of vintage model in which vintages are distinguished only in terms of their capital cost. Technologies of production in (1) are common to all vintages. Oulton (2007) emphasises that ISTC is simply the result of faster TFP growth in a sector producing investment goods than in the a sector producing consumption goods. Our point is that in a multisector model, corrections will have to be made in down-stream sectors to account for errors in the transmission of up-stream TFP changes caused by aggregation. For capital goods, these corrections should take the form of ISTC.

Demand for investment

The accumulation of capital embodying sector-specific technologies involves no different theory to the accumulation of a generic economy-wide capital stock. The expected rate of return in each sector, after adjusting for any sector-specific differences in risk, should be equalised across sectors. The expected rate of return plus the depreciation rate, which could also be sector-specific, should equal the expected gross rental rate. The risk-adjusted rate of return should cover the market interest rate and expected obsolescence costs. These latter account for the relative decrease (or if negative, increase) in the relative price of sector-specific capital from one period to the next. Risk-adjusted rates of return may converge only gradually towards equality if there are real or financial adjustment costs of capital adjustment.

There is good empirical evidence to support differentiating depreciation rates by sector, although very few CGE models do so.[4] Considering different electricity generation technologies, average service lives of e.g. wind turbines and photovoltaic panels are clearly shorter than those of e.g. thermal power plants or hydroelectric dams. More broadly, the KLEMS database (O'Mahony & Timmer, 2009) shows that the composition of capital in terms of broad asset classes differs markedly by sector. In addition, the KLEMS database contains sector-specific depreciation rates for several of the individual asset classes. Lower or higher depreciation rates imply slower or faster turnover of capital and diffusion of capital-embodied technology.[5] They also imply that changes in the sectoral composition of investment will alter the effective aggregate rate of depreciation.

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[4] One example of a model with sector-specific depreciation rates is Bhattarai (2007).

[5] In addition, lower depreciation rates imply that non-negativity constraints on sectoral investment are more easily binding in response to large negative shocks.

In a Ramsey type model in which agents have perfect foresight, the embodiment of technical change affects the user cost of capital. Of particular relevance here, capital-embodiment of rapidly improving technologies creates obsolescence costs that increase the user cost of capital so long as the improvements continue. So for example, a step increase in the rate of technical change in the manufacture of solar PV equipment leads to (i) an increase in the rate at which the purchase price of an efficiency unit of PV equipment capital is falling and (ii) a step increase in the capital rental rate per efficiency unit. While the former effect will dominate in the long run, the latter effect may do so in the short run. Thus, an acceleration of productivity growth may temporarily depress investment.

At the other extreme, recursive dynamic models in which agents have myopic expectations (essentially assuming that future prices will be the same as current prices) *ex ante* obsolescence costs are ruled out by assumption, although obsolescence costs will still be realised *ex post*. In these models, some mechanism whereby rates of return are equalised gradually is a practical necessity. Despite the limitations of recursive dynamic models for studying investment behaviour, they are still widely used because they enable much greater regional and sectoral disaggregation. In the next section we describe modifications of the Intertemporal Computable Equilibrium System (ICES) model to account for the accumulation of sector-specific capital with investment-specific technical change.

Application in the ICES model

ICES-K model

The standard ICES model builds upon the Global Trade and Analysis Project (GTAP) model (Hertel, 1997) and on the extensions of that model to energy and the environment in GTAP-E (Burniaux & Truong, 2002). The latter incorporates a more detailed description of energy use, as well as CO_2 emissions linked to fossil fuel combustion. The current version of ICES is calibrated to a version of the GTAP v8.0 database, enhanced to provide additional detail of energy supply and use. Capital is homogenous and perfectly mobile between sectors. Regional savings are a constant share of regional income, but may be allocated to investment in different regions as a function of relative rates of return. A detailed and up-to-date description of the structure of the standard ICES model can be found in Parrado and De Cian (2014).[6]

In ICES-K, capital stocks and investment are made sector-specific. For each region s and sector j, the next period's capital stock $K_{s,j,t+1}$ is given as a function of the last period's stock $K_{s,j,t}$ and the difference between the current risk-adjusted rate of return[7] to this type of capital $r_{s,j,t}$ and the global average rate of return r_W:

$$K_{s,j,t+1} = \varphi_{s,j} K_{s,j,t} \exp\left(\rho_{s,j}\left(r_{s,j,t} - r_W\right)\right). \quad (3)$$

The parameter $\rho_{s,j}$ controls the speed at which a capital stock responds to any divergence in returns. The parameter $\varphi_{s,j}$ defines the growth rate of the capital stock when rates of return are equalised.

We calibrate the model so that it will reproduce a globally balanced growth path with an equilibrium growth rate of 2% p.a. and therefore choose $\varphi_{s,j} = 1.02$. We choose $\rho_{s,j} = 0.9$, meaning that a +1% interest rate differential will yield an additional 0.9% of growth in the capital stock at the end of the same year. This is essentially the same mechanism that is used in the standard ICES to allocate global savings to finance the aggregate investment in each region except that we use sectoral capital stocks instead of regional GDP on the right hand side of the equation.

Region- and sector-specific geometric depreciation rates are estimated from the depreciation rates contained in the KLEMS database (O'Mahony & Timmer, 2009). This database includes estimates of stocks of eight types of capital in thirty sectors for the United States and a number of European and other developed countries. These are: (i) residential structures, (ii) non-residential structures, (iii) transport equipment, (iv) information technology equipment, (v) communications equipment, (vi) other machinery and equipment, (vii) software and (viii) other fixed capital assets. Associated

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[6] That paper also describes additions to the ICES model to study knowledge spill-overs, which we do not consider here.

[7] For simplicity, we abuse terminology here by using the term 'risk-adjusted' to cover not just risk but also other reasons for which investors may demand a premium in the *pre-tax* rate of return. Differences in tax treatments of different forms of capital income are one such reason.

with each class of assets are depreciation rates. The authors of the KLEMS database assumed these rates to be common to all countries but to vary by sector for capital classes ii, iii, vi, and viii. [8]

We first construct weighted average depreciation rates for each of the KLEMS sectors in each KLEMS country. As weights, we use the stock of each type of capital for that sector and country. We then use concordances constructed between KLEMS sectors and ICES sectors and between KLEMS countries and 16 ICES countries and regions to assign these depreciation rates to sectors in our initial 16-region database.[9] Subsequently, we double the depreciation rates of capital in the solar and wind sectors, which like all other ICES electricity sectors, were mapped to the KLEMS sector 'electricity, gas and water'. Our justification for this is that operating lifetimes for wind turbines and PV modules are 20-30 years, whereas operating lifetimes of fossil-fuelled and nuclear power plants are more typically 40-60 years. Hydroelectric facilities have even longer lifetimes.

Given equation (3) and depreciation rates $\delta_{s,j}$ determined as above, gross investment $Z_{s,j,t}$ in each sector is given by

$$z_{s,j,t} = \frac{1}{a^{Z}_{s,j,t}}\left[k_{s,j,t+1} - \left(1-\delta_{s,j}\right)k_{s,j,t}\right]. \tag{4}$$

The parameter $a^{Z}_{s,j,t}$ defines the (exogenous) level of investment-specific technical change. In this specification, one unit of the raw homogeneous regional investment good is converted to $a^{Z}_{s,j,t}$ units of the sector-specific investment good.

If the price of the raw investment good is $q_{s,t}$, the price of the sector-specific investment good is $q_{s,t}/a^{Z}_{s,j,t}$ and the capital rental price is

$$r_{s,j,t} = \left(i + \pi_{s,j} + \delta_{s,j}\right)\left(q_{s,t}/a^{Z}_{s,j,t}\right), \tag{5}$$

where i is the risk-free rate of return and $\pi_{s,j}$ are constant risk premia. We calibrate regional risk premia for each of our original 16 regions such that aggregate investment and capital rents are consistent, assuming that all capital stocks are growing at the equilibrium balanced growth rate.

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[8] They are based in turn on depreciation rates estimated for the US.

[9] The sixteen regions are: USA, Canada, Japan, South Korea, Australia and New Zealand, France, Germany, Italy, UK, six multi-country regions within Europe and the Rest of the World.

For the purpose of producing illustrative results in this paper, we aggregate the 16-region database to just four regions: USA, Europe, Rest of OECD and Rest of World. To maintain consistency with the data, implied risk premia in the (newly) aggregated Europe and Rest of OECD regions are sector-specific.

In ICES-K, we abandon the assumption in ICES (introduced in the GTAP-E model) that capital and energy are direct complements in favour of the more common assumption that capital is complementary to a composite of capital and labour. This change reduces the importance of the reallocation of capital between sectors and regions as a margin of adjustment to carbon pricing. Our current specification is more consistent with the view that in the long run and in general, capital may be either energy-saving or energy-using, depending on relative prices of other inputs.

Finally, we increase elasticities of substitution between different types of electricity generation to allow a more realistic long-run response of the energy system to carbon pricing. Due to limitations of the current model structure, the result is not entirely satisfactory, but sufficient for illustrative purposes here. In future work we will revise the structure of the model to improve representation of the electricity sector. In particular, to allow for realistically high (or infinite) long-run elasticities of substitution between different sources of electricity on the demand side, constraints on the supply of individual technologies and/or the mix of technologies must be incorporated. Additionally, the current user-specific composites of electricity will be eliminated in favour of common production functions. This will simplify the model and also eliminate a current problem in the way that electricity enters into the household demand system.

Specifying technology scenarios

Multi-decadal baseline scenarios are routinely developed by CGE modellers following what could be characterised as a generally accepted but imprecise methodology. In practice, heavy reliance is placed on external projections of population, GDP and other macro variables, usually taken from official national or intergovernmental sources as appropriate. These aspects of scenario development are rarely controversial, although it can be argued that different sources sometimes embody contradictory underlying assumptions. Recent integrated and transparent approaches to developing long-term macroeconomic projections (Fouré, Bénassy-Quéré, & Fontagné, 2013) should therefore be welcomed.

Incorporating sector-specific technical changes in long-run scenarios for multisector CGE models is crucial, but doing so in an empirically informed and transparent way is particularly difficult. Technical changes biased towards factors in fixed or inelastic long-run supply are necessary if rapidly increasing scarcity rents are to be avoided. Particularly in the context of climate change, much concern focusses on the supply and use of fuels and electricity. Failure to account for the rapid progress in wind and solar energy technologies would cause models to greatly over-state the costs of climate change mitigation, as would failure to account for the widespread improvements in energy end-use efficiencies. The latter even has its own acronym in the climate policy modelling literature: AEEI or autonomous energy efficiency improvement.

Using datasets such as KLEMS and the World Input-Output Tables (Dietzenbacher, Los, Stehrer, Timmer, & de Vries, 2013), it is possible to comprehensively estimate historic changes at the sector level and even to partially disentangle input-embodied from disembodied technical change. However, it is difficult to plausibly extrapolate such historic trends very far into the future. Moreover, such 'top-down' sources do not distinguish many of the technologies that we are most interested in. In practice, CGE modellers usually draw on a combination of sources to directly specify specific productivity parameters or to adjust them to target related baseline prices or quantities. These sources include simple extrapolations of historic productivity trends, other researchers' judgement- or model-based projections of future technology trends, and other researchers' modelling or extrapolation of prices or quantities. The first two approaches are prevalent in the case of agriculture, specific energy technologies (e.g. solar, wind) and AEEI. The last approach is prevalent in the case of coal, oil and gas extraction. For oil and gas in particular, the complexity and uncertainty of resources, economic reserves together with the complex international market structure make the former approaches untenable.

Progress in renewable energy technologies

Our approach to CGE modelling of sector-specific technical changes is general, flexible and simple to operationalise. However, as discussed above, applying the approach to all technologies is empirically problematic. Given this difficulty, we turn our focus to a narrow but relevant problem of modelling technical change in specific energy technologies. For illustrative purposes, we consider capital-embodied technical progress in only solar and wind electricity generation, two technologies in which costs have fallen dramatically over several decades.

A standard approach in CGE modelling of climate policies is to calibrate energy technology parameters to reproduce baseline projections of energy sector outputs generated by a detailed energy systems model (e.g. the International Energy Agency's World Energy Model). Energy systems models provide very detailed representations of technologies, usually including some form of vintage capital structure. Thus, they should provide more reliable projections of progress and diffusion of specific energy technologies than CGE models. Taking this approach to calibration, there should be only small differences between the baseline projections of a standard CGE model featuring only disembodied technical changes and a CGE model including ISTC in selected energy technologies. The more interesting question is how much modelling of ISTC might alter the response of a CGE model to carbon prices or other policies.

As our aim is to compare the two specifications rather than produce a realistic baseline scenario *per se*, we do not begin with an exogenous scenario for solar and wind outputs but with an exogenous scenario of ISTC. Thus in the ISTC version of ICES-K we can directly specify technologies, while in the KATC version, we calibrate solar and wind technology parameters to reproduce solar and wind outputs from the ISTC baseline. We take the initial rates of ISTC in solar and wind technologies as 8% and 4% respectively. We assume that these rates follow a logistic function of time, such that they halve by 2020 and have fallen ten-fold by 2031. By the end of the simulations, solar productivity has risen almost 200% while wind productivity has risen over 70%, with about 90% of that progress achieved by 2030. Remaining elements of the baseline scenarios common to both model versions are described in appendix 1.

Results

Baseline scenarios

As we make the same assumptions about solar and wind technologies and carbon prices in all model regions, we present and discuss results for just one region: Europe. Results for other regions are qualitatively similar. The exogenous improvements of capital-embodied wind and solar technologies drive two- and three-fold increases over three decades in European wind and solar electricity production respectively (Figure 1). Given the simplicity of the model as concerns modelling of energy technologies and of our calibration approach, these should *not* be seen as realistic projections. Nevertheless, they provide context for the remainder of our analysis. The exogenous improvements in embodied solar and wind technologies in the ISTC case are shown in Figure 3. Also shown are the calibrated disembodied productivity improvements in solar and wind technologies. As explained above, the calibrated values allow solar and wind outputs in the ISTC baseline to be replicated in the KATC baseline.

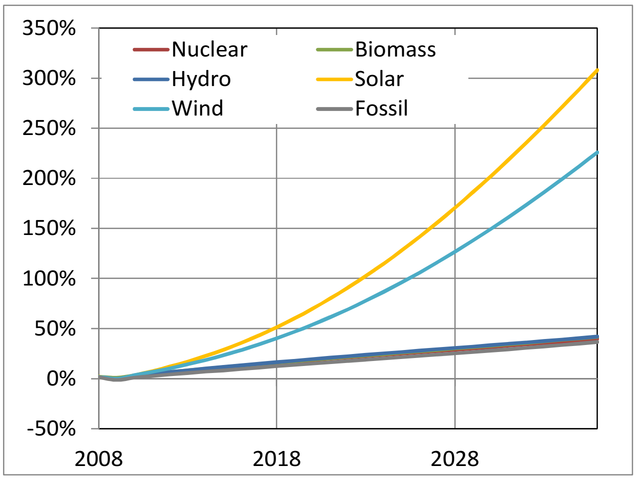


Figure 1 – Baseline electricity outputs in Europe (% change from base year).

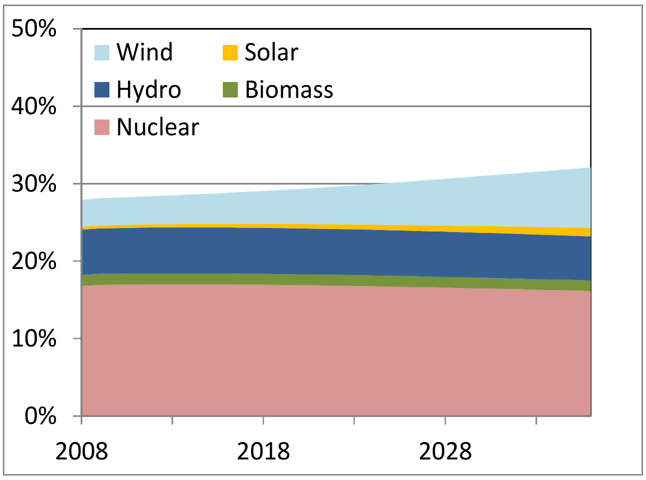


Figure 2 – Baseline shares of non-fossil electricity in Europe.

Capital rental rates and rates of return respond very differently to investment-specific and capital-augmenting technical change (Figure 4). In the ISTC version, technical change lowers the replacement cost of solar and wind capital. This directly increases their capital rental rates and so drives an increased demand for investment in those sectors. It should be noted that lower replacement costs impose obsolescence costs on owners of old solar and wind capital. However, because agents act myopically in ICES-K, those costs are sunk and do not affect investment demands.

In the KATC version, capital-augmenting technical increases the effective supply of solar and wind capital. To clear the capital market, solar and output increases, as was shown above. Output demand is very elastic, so although this pushes down output prices, it does not do so by as much as technical change directly reduces input costs. Since solar and wind producers would otherwise earn excess profits, they reduce the ratio of their variable inputs to capital. This pushes up capital rental rates until excess profits are eliminated.

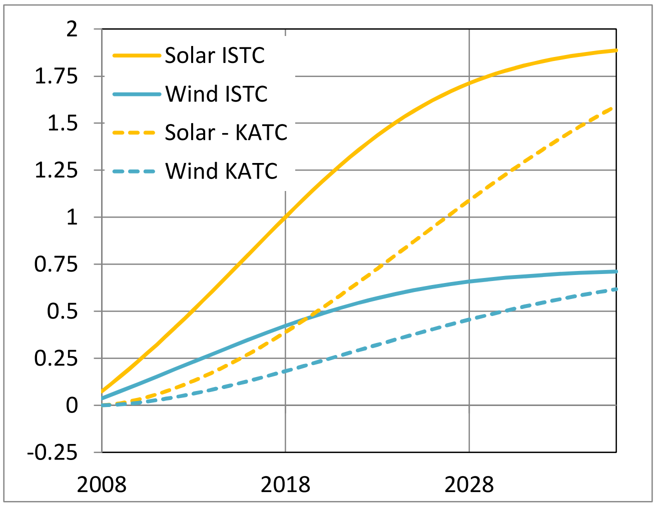


Figure 3 – Exogenous paths of ISTC and calibrated paths of KATC for solar and wind in Europe.

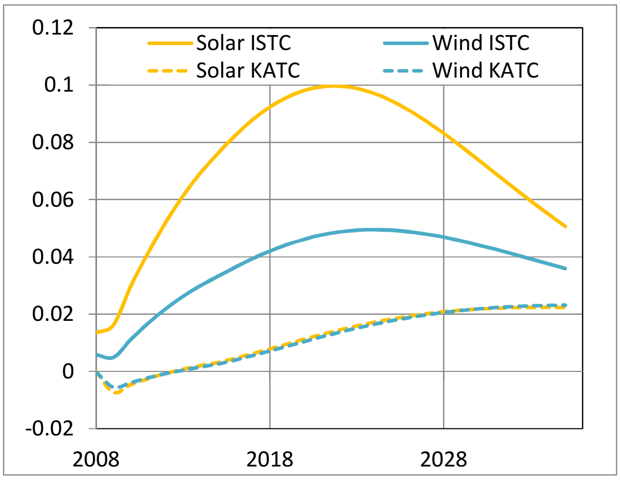


Figure 4 – Rate of return differential for solar and wind capital (percentage points w.r.t. global rate of return).

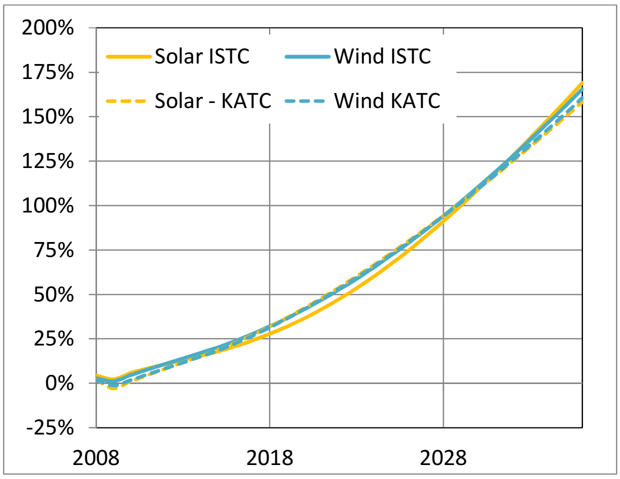


Figure 5 – Solar and wind investment expenditures in ISTC and KATC baselines (% change from base year).

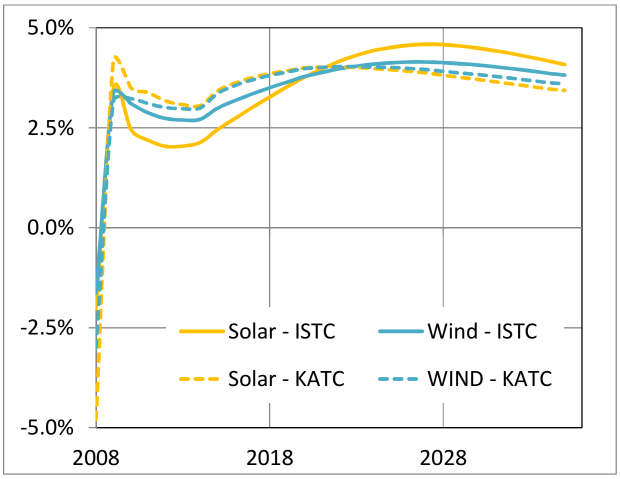


Figure 6 – Growth rates of solar and wind investment expenditures in ISTC and KATC baselines.

Due to input substitution possibilities in the solar and wind sectors, replication of the paths of solar and wind output does not imply exact replication of the paths of solar and wind capital, nor therefore of investment expenditure. Small deviations in investment expenditure can be seen plotting the percentage change in levels of investment expenditure (Figure 5). Plotting investment expenditure growth rates highlights the fact that growth rates are lower in the first half of the simulation but higher in the second half in the ISTC baseline compared to the KATC baseline.[10] These differences in solar and wind capital and investment in turn have general equilibrium effects. However, because solar and wind output is initially and (in our scenarios) remains a small part of the energy sector and an even smaller component of the aggregate economy, general equilibrium effects are extremely small.

Carbon pricing

The most interesting questions concern the way in which the modelling of technical change affects responses to alternative policies. To illustrate these differences we consider a highly stylised climate change mitigation policy: we impose a globally uniform and rising carbon price imposed on all CO_2 emissions from energy use. Existing as well as proposed climate policies are omitted for simplicity. The carbon tax begins at US_{2007}\$13 in 2008 and rises 25% p.a. in the next three years to reach \$25 in 2011.[11] From 2011, the carbon price rises at a constant rate of 6.5% per annum to reach US_{2007}\$122 in 2036.

Output (Figure 7) increases more slowly in response to carbon pricing in the ISTC model than in the KATC model. These differences are relatively larger for solar, which has a higher rate of productivity growth than for wind, which has a lower rate. Again, these differences can be seen more clearly by plotting growth rate differentials (Figure 8). Fossil electricity generation naturally declines in response to carbon pricing, while nuclear (as well as hydro and biomass, which respond similarly) generation increases, but by a much lesser percentage than either solar or wind, which benefit from technical change (Figure 9). The nearly symmetric responses of the mature generation technologies reflects the current ICES-K model structure in which there are constant elasticities of substitution between technologies and no supply-side constraints.

[10] Negative growth in the first years is unrelated to the technical changes and is caused by the great recession.

[11] We ramp up the tax in this way rather than choosing a higher initial carbon price so that sectoral investments remain non-negative. A zero lower bound on sectoral investments can be enforced in the model, but including the associated complementarity conditions greatly reduces simulation speed.

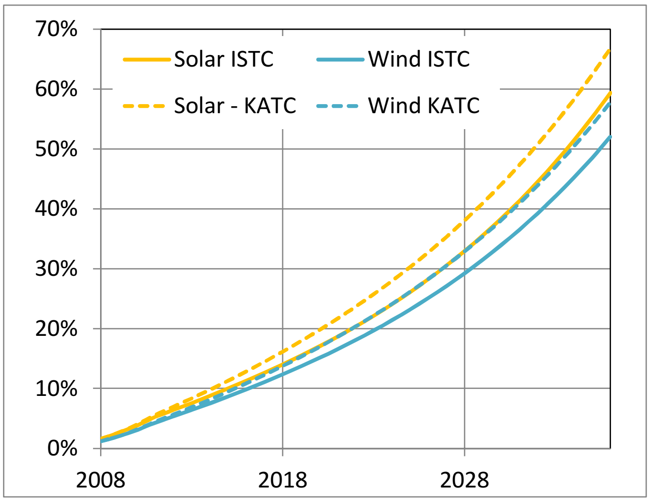


Figure 7 – Change in output of solar and wind electricity in Europe (% change from baseline).

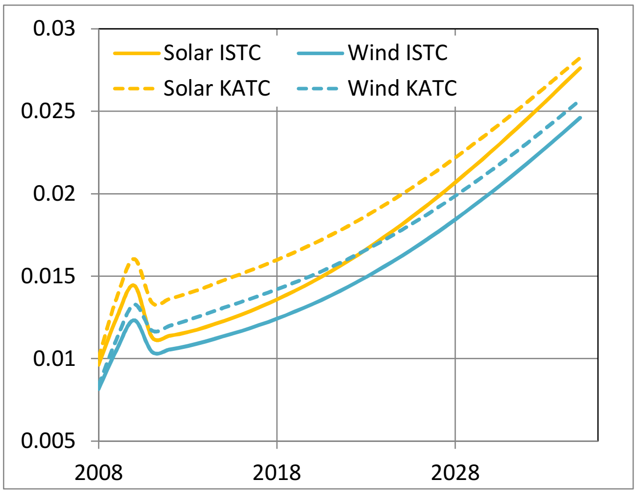


Figure 8 – Output growth rate differentials w.r.t. baseline growth rates.

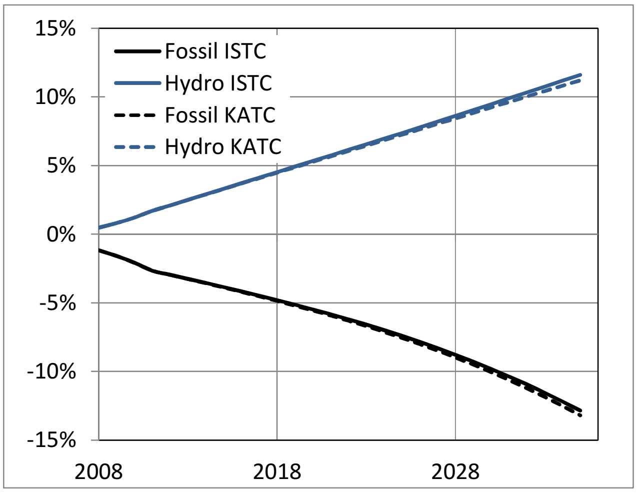


Figure 9 – Change in output of fossil and nuclear electricity in Europe (% change from baseline).

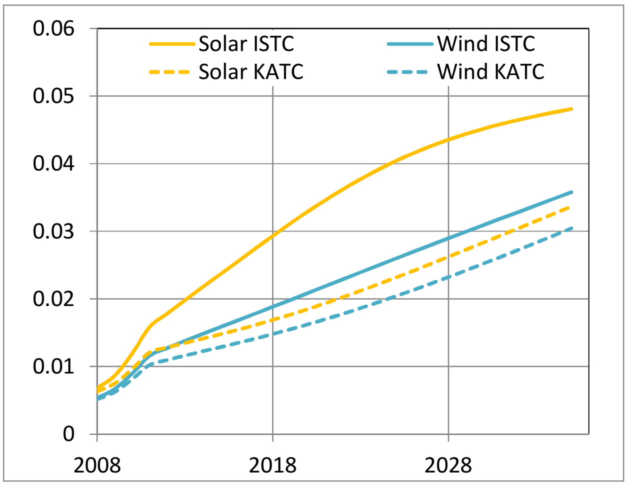
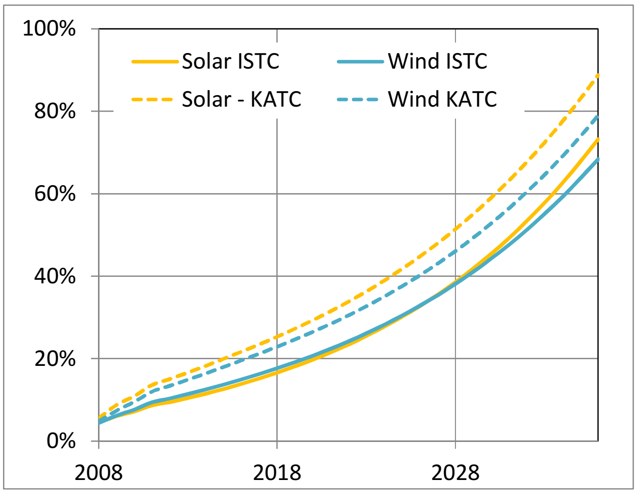


Figure 10 – Rate of return differential for solar and wind capital (percentage points w.r.t. to baseline rates)

Figure 10 shows the increases in rates of return for solar and wind capital. Increased demand for solar and wind generation increases demand for these types of capital. In both the ISTC and KATC versions of the model, higher rates of return drive increased capital accumulation and investment (Figure 11). However, increasing investment in the ISTC version does not simply increase the quantity of capital but simultaneously the average productivity of the capital stock, which in the KATC version was exogenously fixed in the calibration stage. Investment growth rate differentials are shown in Figure 12, which highlights the lower initial but more rapidly accelerating growth of investment in the ISTC version compared to the KATC version.



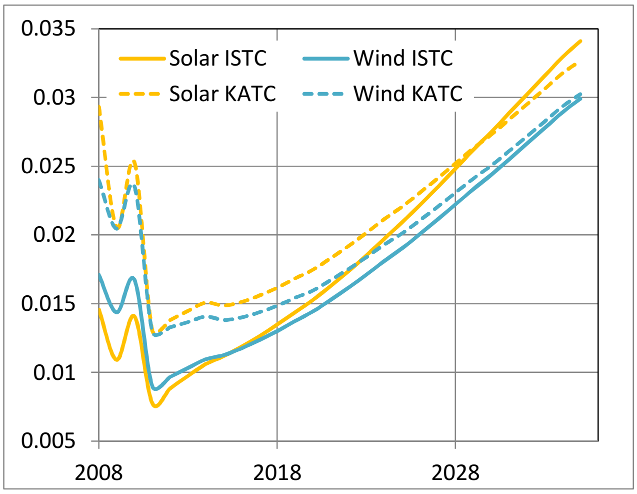
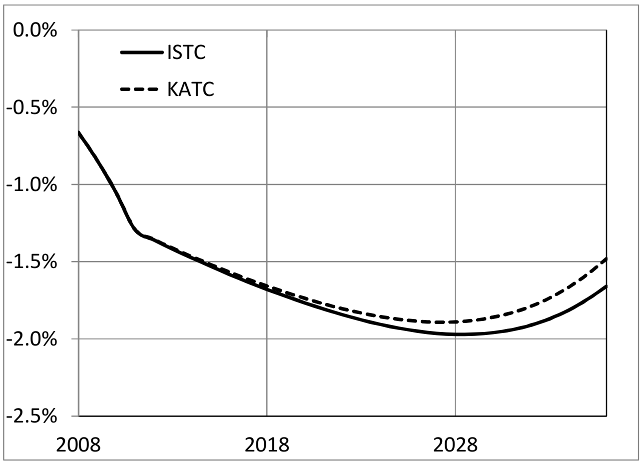


Figure 11 – Change in investment expenditures of solar and wind electricity in Europe (% change from baseline).

Figure 12 - Investment expenditure growth rate differentials w.r.t. baseline growth rates.

Overall output and emissions from the electricity sector relative to the baseline are shown in Figure 13 and Figure 14 respectively. Output is only slightly higher and emissions slightly lower in the KATC version than in the ISTC version. This relative insensitivity of aggregate sectoral variables to the alternate model specifications is explained by the combination of the modest differences in solar and wind outputs found above and the low shares of these technologies in the baseline generation mix.



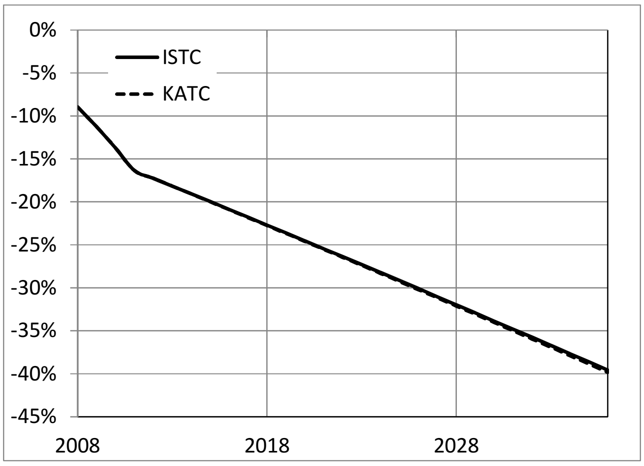


Figure 13 – Electricity sector output in Europe (% change from baseline).

Figure 14 – Electricity sector emissions in Europe (% change from baseline).

Comparing the two figures, it is seen that in the current model specifications, the net response of the electricity sector to carbon pricing is decarbonisation rather than output reduction. This is explained by both supply- and demand-side responses. Within the electricity sector, there are possibilities to substitute capital for fossil fuel inputs (representing energy efficiency), to substitute between fossil fuel inputs (representing a changing fossil generation mix) and to substitute carbon-free for fossil generation. On the demand side, output losses are mitigated by substitution in other sectors of electricity for fossil fuels. Finally, globally uniform carbon pricing mitigates negative income effects in Europe, because capital is reallocated to Europe from regions with high carbon intensities of production.

Discussion and conclusions

In multisector CGE models, sector-specific technological changes are usually modelled as disembodied, augmenting some or all factor or intermediate inputs. We have shown that capital-embodiment of Hicks-neutral innovations can arise naturally in a multisector CGE framework in which production sectors and investment goods are suitably disaggregated. Unfortunately, empirical and computational difficulties make it difficult to argue against the conventional CGE modelling approach in which there is an aggregate investment good. This precludes changes in sector-specific and capital-embodied technologies arising endogenously. However, 'missing' capital-embodied technical change can be reintroduced exogenously as ISTC. This approach is simple to implement and has no obvious computational costs in a CGE model in which capital stocks are already sector-specific.

Effects of capital-embodiment are inherently dynamic. When levels of technology are held constant, the ISTC and KATC models give the same long run result. However, differential rates of technological change can persist over decades, as can dynamics due to capital stock turnover. Thus, the dynamic effects are long-lasting and therefore are potentially important when analysing responses to climate policies. Differences will also be greater the lower the depreciation rates of the capital goods concerned. In ICES-K we departed from the usual assumption that all capital depreciates at a common rate. Data on the composition of sectoral capital stocks and associated estimates of depreciation provide one way of estimating heterogeneous depreciation rates.

The ISTC approach appears particularly useful for modelling scenarios featuring rapid progress in a specific set of capital-embodied technologies; for instance, energy technologies. Our illustrative simulations results using the ICES-K model show that a conventional CGE model featuring disembodied sector-specific technical change can give similar results to an otherwise comparable CGE model featuring investment-specific technical changes. However, this result is conditional on relevant technical parameters being calibrated to reproduce exogenously given baseline outputs. In the context of climate policy modelling, that is a practically relevant but not universally applicable approach to developing a baseline scenario. Our negative results also depend on the changes in average productivity levels induced by policies being limited in magnitude and scope. We considered ISTC in only the solar and wind electricity sectors. Moreover, we did so in a model that is not currently well-suited to modelling a wholesale technological transition that would decarbonise electricity production.

In a recursive-dynamic model such as ICES-K, the obsolescence costs generated by capital-embodied technical change are always seen as sunk and so do not affect investment decisions. In a model in which agents have forward-looking expectations, an increase in obsolescence costs resulting from an increase in the rate of ISTC has a negative effect on investment in the short run but a positive effect in the long run (Lennox & Witajewski, 2014).

Another issue that we have not addressed here is the feedback from investment to technology. Most energy-focussed climate policy models allow for Learning-by-Doing (LbD) in newer technologies, including solar and wind (Luderer et al., 2012). Investment in capital goods may also interact with investment in research on and development of capital-embodied technologies (Lennox & Witajewski, 2014). Our version of the ICES-K model with ISTC could be easily extended to allow for LbD in selected capital-embodied technologies.

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Appendix 1 – Baseline

Our baseline scenario is constructed using projections of population, labour force and total factor productivity (TFP) by region of Fouré *et al.* (2013). In addition, we allow for relatively slower growth in the supply of natural resources and/or resource-augmenting technical change. However, in the baseline, new energy technologies (solar and wind electricity) benefit only from the general improvements in labour productivity. Finally, we allow for autonomous energy efficiency improvements (AEEI) in all energy end uses. Growth rates of AEEI are falling over time, reflecting thermodynamic and other technical limits to this type of input-augmenting technical change.

To produce the preliminary results presented here, we have used *ad hoc* adjustments based on the original TFP projections and qualitative factors (e.g. the scarcity of oil relative to coal resources). For the final version of this paper, we will calibrate many of these parameters to match the originally projected GDP and, so far as possible, compatible energy supply and price projections of the International Energy Agency.

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