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DISCUSSION PAPER

Economic and Environmental impacts of Carbon Taxes in East Asia to Meet the 2050 2℃Targets :

An analysis using E3ME-FTT model

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Abstract:

The Paris Agreement (PA) has set long-term targets for decarbonisation around the world. Most countries have now pledged contributions to reducing emissions through their Nationally Determined Contributions (NDCs) submitted to the UN. Some countries have also set long-term emissions reduction targets for 2050 that are in line with the commitments in the PA.Policy makers now face the question of how best to reduce emissions, while still promoting economic development and national prosperity. In this paper we assess a range of options and show that a combination of instruments is likely to produce the best results for national economies in East Asia. Our modelling approach shows that implementing a mix of measures could reduce the necessary carbon price required to meet long-term emission reduction targets, benefitting energy-intensive industries. Our conclusion is that the modelling tools used by economists must be able to assess a range of different policies, so as to meet the current requirements of policy makers.

Key words:

East Asia, 2050 2℃targets, Carbon Taxes, E3ME Model

1 Introduction

The Paris Agreement (PA) represented a major breakthrough in global climate policy. The PA provides the framework in which all climate policy now takes place. Most countries have targets for 2030 (or in some cases other years in similar timeframes) to reduce greenhouse gas emissions. Despite one major country intending to leave the agreement, there remains a consensus that the world should be moving towards net-zero emissions in the second half of the 21st century.

East Asia will play a major role in determining the eventual success of limiting global warming to substantially less than 2°C. China is the world's largest emitter but is increasingly being seen as a global leader in building renewable power sources. The other economies in East Asia each face their own unique challenges in meeting emission reduction goals.

Policy makers now face several challenges:

- How to determine the policies to meet their NDC commitments
- How much to 'ratchet' up NDC ambition levels, starting at the 2019 Conference of the Parties (COP).
- How to determine long-term targets for emission reductions (i.e. after 2030).
- How to decarbonise economies while still expanding prosperity across the region.

Modelling tools can be helpful to policy makes in assessing the policies that they must implement to meet carbon reduction targets. However, it is noted that many of the most widely used modelling tools have a rather limited range of policy options available within them. In particular, optimisation frameworks are often restricted to considering price-based options with a focus on carbon pricing. From a policy maker's perspective, carbon pricing may not be the most attractive, or even a feasible, option, for example due to competitiveness impacts or effects on social welfare and energy poverty.

In this paper we present scenarios from a modelling framework that covers a much broader range of policy options. Furthermore, it is a modelling framework that is specifically designed to assess policy, based on simulated responses to policies rather than using assumptions based on optimising behaviour that have been repeatedly disproven in behavioural literature (e.g. Kahnemann, 2012).

We apply the modelling framework to a set of carbon reduction targets for East Asia, and show that regulatory policies can work alongside carbon prices to achieve larger emission reductions; and can also mean that lower carbon prices are needed to meet a fixed target. Ultimately, the impacts on national economies could be reduced by adopting a broad portfolio of policies.

The next section describes the modelling framework. The following sections present the scenarios and the impacts on emissions and national economies. The final section concludes.

2 Modelling approach

2.1 Introduction

In this analysis we apply a macroeconomic model, E3ME, that incorporates bottom-up sub-models with a high level of technological detail. E3ME is a macro-

econometric model that is post-Keynesian in design and differs substantially from the more common Computable General Equilibrium (CGE) approach. In this section we describe the model and its FTT (Future Technology Transformations) sub-models of energy technologies. The final part of this section compares the approach to that of a standard CGE model.

For a more detailed description of E3ME, the reader is referred to the model manual (Cambridge Econometrics, 2014) on www.e3me.com. The general assessment methodology is described further in Mercure et al (2016) and a full list of equations is provided in Mercure et al (2018a).

2.2 The E3ME model

E3ME is a computer-based model of the world's economic and energy systems and the environment. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes. The global edition of E3ME includes 59 regions. It incorporates the global capabilities of the previous E3MG model.

In this analysis we focus on four regions in East Asia. They are China, Japan, Korea and Taiwan. Each is defined explicitly in the E3ME model.

Each national economy in E3ME is disaggregated into 43 economic sectors. The sectors are linked using input-output coefficients and the different regions through bilateral trade relationships. Table 1 summarises the main dimensions of the model.

Table 1 Main dimensions of E3ME

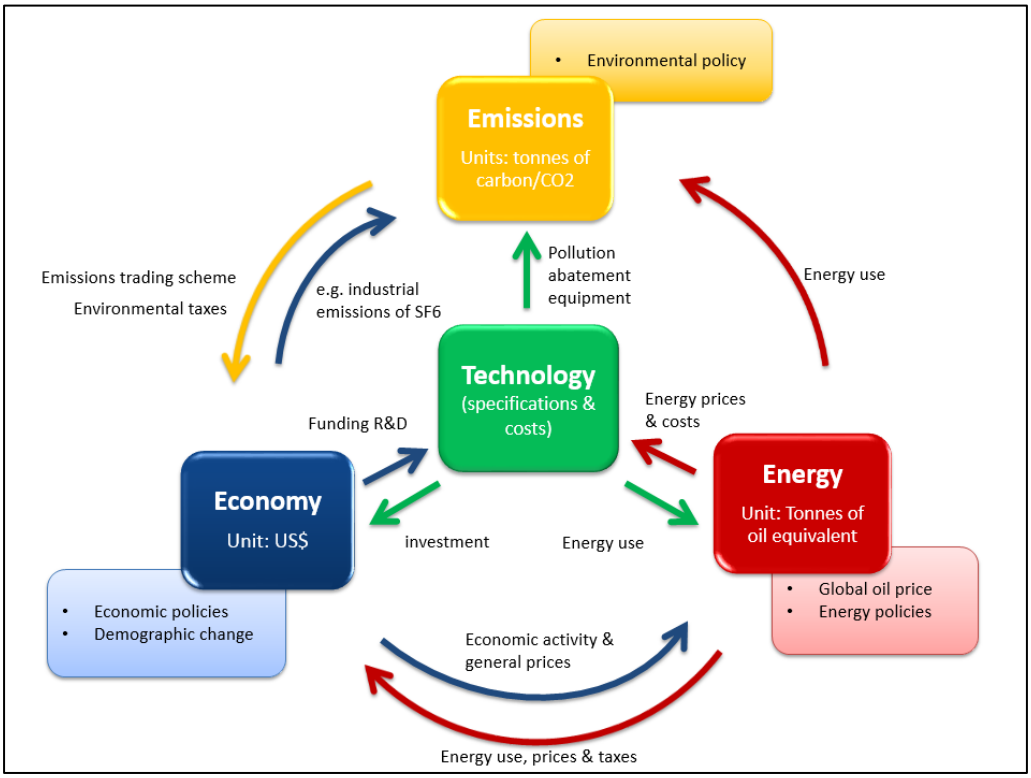
Dimension	Description
Regions	59, which aggregate to global totals.
Sectors	43, based on standard industrial classifications.
Time horizon	Annual time steps to 2050. Historical data go back to 1970.
Energy carriers	12 types.
Emissions	14 types, including all GHGs.

The main data sources for the East Asian regions in E3ME are the OECD and national statistical agencies. Energy data are taken from IEA statistics and emissions data from the EDGAR database. The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. In total there are 33 sets of econometrically estimated equations, also including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each equation set is disaggregated by country and by sector. The following list provides a summary of the most common model outputs:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- sectoral output and GVA, prices, trade and competitiveness effects
- international trade by sector, origin and destination
- consumer prices and expenditures
- sectoral employment, unemployment, sectoral wage rates and labour supply
- energy demand, by sector and by fuel, energy prices
- CO_2 emissions by sector and by fuel
- other air-borne emissions
- material demands

The acronym 'E3ME' stands for 'Energy-Environment-Economy Macro-Econometric' model. Figure 1 provides an overview of the main interactions between the different components of the model.

Figure 1 Structure of the E3ME model



Within each module, each data set has been constructed to conform with accounting conventions; physical units are used for energy consumption and emissions. Exogenous factors coming from outside the modelling framework are shown on the outside edge of the chart as inputs into each component. For each region's economy the exogenous factors are economic policies (including tax rates, growth in government expenditures, interest rates and exchange rates). For the energy system, the outside factors are the world oil prices (determined endogenously within the model but not much influenced by any single country) and energy policy (including regulation of the energy industries). The linkages between the components of the

model are shown explicitly by the arrows that indicate which values are transmitted between components.

The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides measures of emissions of the main air pollutants to the environment module. The energy module provides detailed price levels for energy carriers distinguished in the economy module and the overall price of energy as well as energy use in the economy.

Technological progress plays an important role in the E3ME model, affecting all three Es: economy, energy and environment. The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment. In addition, E3ME also treats technologies in several key sectors explicitly through the bottom-up FTT models (see below).

The econometric techniques used to specify the functional form of the equations are the concepts of cointegration and error-correction methodology, particularly as promoted by Engle and Granger (1987) and Hendry et al (1984). In brief, the process involves two stages. The first stage is a levels relationship, whereby an attempt is made to identify the existence of a cointegrating relationship between the chosen variables, selected on the basis of economic theory and a priori reasoning. If a cointegrating relationship exists then the second stage regression is known as the error-correction representation, and involves a dynamic, first-difference, regression of all the variables from the first stage, along with lags of the dependent variable, lagged differences of the exogenous variables, and the error-correction term (the lagged residual from the first stage regression).

Due to limitations of data size, however, only one lag of each variable is included in the second stage. Stationarity tests on the residual from the levels equation are performed to check whether a cointegrating set is obtained. Due to the size of the model, the equations are estimated individually rather than through a cointegrating VAR. For both regressions, the estimation technique used is instrumental variables, principally because of the simultaneous nature of many of the relationships.

2.3 The FTT family of models

The most important energy-using sectors are represented using a novel framework for the dynamic selection and diffusion of innovations that was developed by J.-F. Mercure (Mercure, 2012). These are the FTT models. They are applied for:

- The power sector (Mercure, 2012)
- Passenger car transport (Mercure et al, 2018b forthcoming)
- Household heating (Knobloch et al, 2018 forthcoming)

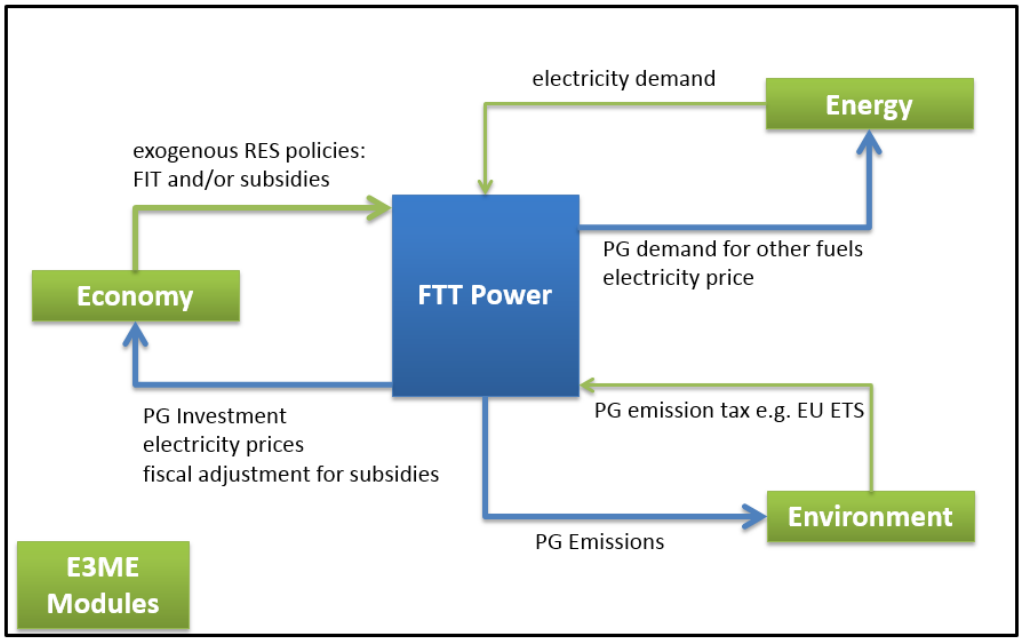
Further FTT models are currently under development for several industrial sectors and the agricultural sector.

The FTT models use a decision-making core for investors who are purchasing new equipment (e.g. power generation capacity, vehicles). The decision-making core takes place by pairwise levelised cost (LCOE) comparisons, conceptually equivalent to a binary logit model, parameterised by measured technology cost distributions. Costs

include reductions originating from learning curves, as well as increasing marginal costs of renewable natural resources (for renewable technologies) using cost-supply curves. The diffusion of technology follows a set of coupled non-linear differential equations, sometimes called 'Lotka-Volterra' or 'replicator dynamics', which represent the better ability of larger or well established industries to capture the market, and the life expectancy of technologies. Due to learning-by-doing and increasing returns to adoption, it results in path-dependent technology scenarios that arise from a full range of sectoral policies.

The resulting diffusion of competing technologies is constrained by a global database of renewable and non-renewable energy resources (Mercure and Salas, 2012, 2013), which also feed back commodity prices to the econometric equations in the rest of the E3ME model. Figure 2 provides an example of how the FTT models are linked to E3ME.

Figure 2 Model linkages



2.4 Previous applications of E3ME

Mercure et al (2018c) and Holden et al (2018) describe the most recent global scenarios of 2°C and 1.5°C that have been assessed with the E3ME model. These scenarios do not pay specific attention to the East Asian region, but provide the global context for the present analysis, for example by setting the assumptions for the rest of the world in the policy scenarios.

Within East Asia, E3ME has also been used extensively. The model was central to the analysis in *Low-Carbon Sustainable Future in East Asia* (Lee et al, 2016), in which it was used to assess power sector reform, environmental tax reform and trade agreements. In Japan, E3ME has been used repeatedly to study the potential impacts of carbon taxes in the period up to 2030 (Lee et al, 2017; Pollitt et al, 2014; Lee et al, 2012). This paper is the first time that the model has been used to assess policies out to 2050 in East Asia, however.

E3ME is also used frequently for policy assessments. In the past year the model has been used for work the Japanese Ministry of Environment and it has been used for several major policy assessments in the European Union. A recent global study for IRENA outlined an alternative pathway towards 2°C (IRENA, 2018).

2.5 Comparison with the CGE approach

E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this there are important theoretical differences between the modelling approaches.

In a typical CGE framework, optimal behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME the determination of output comes from a post-Keynesian framework. The starting point is the assumption that (in contrast to the CGE approach), agents do not have perfect knowledge and therefore cannot optimise their behaviours. Similarly, markets may not adjust perfectly through movements in prices.

As a result, it is possible to have spare capacity in the economy. The model is more demand-driven and it is not assumed that prices always adjust to market clearing levels. In addition, as described in Pollitt and Mercure (2017), there is not a fixed supply of money in E3ME, reflecting the real-world observations from central banks (e.g. McLeay et al, 2014).

The differences have important practical implications, as they mean that in E3ME regulation and other policy may lead to increases in output if they are able to draw upon spare economic capacity. This is described in more detail in the model manual.

The econometric specification of E3ME gives the model a strong empirical grounding. E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend (see above). The dynamic specification is important when considering short and medium-term analysis (e.g. up to 2020) and rebound effects, which are included as standard in the model's results.

3 Scenarios

3.1The baseline

The starting point for the paper is a standard baseline scenario, based on the Asia/world Energy Outlook (IEEJ, 2017). This forms the reference case to which all the other results will be compared. The E3ME baseline solution is calibrated to the published figures using a set of scaling factors that are then applied to both the reference case and the policy scenarios. The reference case is thus a fully endogenous model solution that is consistent with the IEEJ trends.

For the rest of the world, we assume that policies are put in place that are consistent with a 2°C scenario. East Asia is thus decarbonising in line with the rest of the world and would not be expected to suffer major losses of competitiveness because of implementing new policy. We use the same set of policies as applied in Mercure et al (2018d). It is noted that certain major economies are currently not implementing the necessary policies but our analysis is long-term in nature and we assume that some movement takes place.

3.2 Meeting a 2°C target

The remaining scenarios are based on policy inputs. In each case, the policies are designed to meet a 2°C target. We start off by trying to meet the targets through just a carbon tax (as many neoclassical economists recommend) and then gradually introduce new policies to different sectors, resulting in a lower carbon price.

It is noted that the countries in East Asia do not yet have formal targets for 2050 to be consistent with 2°C, and so we provide our own values. It is also noted that we are combining developed and developing countries (as defined in the UNFCCC's 'annex 1 list') and so differentiated targets would be expected. The carbon reduction targets are given in Table 2.

Table 2 CO_2 reduction targets for 2050 (% from 1990 levels)

China	0% (i.e. return to 1990 levels)
Japan	-80%
Korea	0%
Taiwan	-75%

These targets partly reflect the trends in the reference case, results in Mercure et al (2018d) and initial findings from our model runs. As we shall see in the results, they appear to be toughest for Japan and Korea but not so difficult for China and Taiwan. All the targets are defined in terms of energy CO_2 because the current version of the E3ME model does not have specific policy options for process emissions and does not cover agriculture and land use in a high level of detail.

The scenarios aim to meet the targets by:

- S1: Carbon taxes only
- S2: Power sector regulations and subsidies, plus carbon taxes
- S3: The measures in S2, plus an industrial energy efficiency programme
- S4: The measures in S3 plus incentives to reduce transport emissions
- S5: The measures in S4 plus incentives to decarbonise household heating

Further details of the policy measures are given below.

The carbon taxes are levied on all use of fossil fuels in relation to carbon content. They are additional to any carbon pricing policies that are already included in the baseline. They increase linearly up to 2050. There are no exemptions. In the current version of the analysis, the revenues are not recycled back into domestic economies, meaning that the taxes will have a negative effect on GDP. Even when we introduce policies to other sectors, the carbon taxes are still applied to those sectors, as the policy interactions are important.

The power sector policies are entered into the FTT:Power model:

- Feed-in-Tariffs: FiTs are designed to close the gap between the strike price for electricity and the cost of generating with renewables.
- Direct renewables subsidies: Subsidies on initial capital may boost uptake of renewable technologies.
- There are mandates to prevent new coal power plants being built.

The carbon taxes also apply to the power sector and feed into the levelised cost calculations, based on associated emissions with each generation technology.

The energy efficiency programmes are modelled as mandates imposed by government. The values used match those in the IEA's 450PPM scenario (IEA, 2016). The exogenous inputs to the model are:

- the energy savings (in tonnes of oil equivalent, split across sectors, energy carriers, on an annual basis)
- the investment required to build and install the equipment, in monetary terms

The following policies are applied to the road transport sector in S4 and S5:

- Registration taxes based on the fuel economy of the cars: the taxes are paid upfront when purchasing vehicles.
- Taxes on fuels: this tax is paid on each unit of fuel consumed.
- New vehicle efficiencies are assumed to be upgraded over time.
- Some types of vehicles (e.g. older petrol and diesel vehicles) are phased out and replaced by higher efficiency versions or by alternative propulsion vehicles (EV, CNG, etc). Existing vehicles live to the end of their statistical lifetimes.
- Public procurement measures: it is assumed that some new vehicle technologies are boosted through procurement schemes.
- Biofuel mandates: it is assumed that by 2050 60-65% of liquid fuels are biofuels rather than conventional fuels.

The following policies are put in place on heating:

- Taxes on residential fossil fuel use: the tax is paid on fuel consumption, relative to a fuel's carbon content.
- Direct subsidies for renewables: The subsidies are defined as a share of the capital cost of new heating technologies. They feed into the levelised calculations and are funded by government.
- Public procurement: new heating systems are adopted initially in public buildings.

In all the scenarios, a limit of $1,500 is put in place on the carbon tax rates that may be applied. Although the limit is fairly arbitrary, it is unlikely that such a high carbon tax would ever be levied in reality and model results become too uncertain beyond this point. It is therefore possible for countries to miss their carbon reduction targets.

4 Results

4.1 Impacts on emissions

Table 3 shows the emissions levels in 2050 in each scenario. The figures in the table show the different baseline trajectories for each country in East Asia, and how each country responds to the carbon taxes and the other policies. The results for S1 show

that the carbon taxes can reduce CO_2 emissions substantially in every country, but not by enough to meet the targets that we set (and the maximum carbon prices allowed, see below). All four countries miss their targets.

Table 3 Emissions levels in each scenario, energy CO_2, % from 1990

	China	Japan	Korea	Taiwan
Target	*0*	*-80*	*0*	*-80*
Baseline	437	9	294	254
S1 (C Tax)	29	-74	71	-61
S2 (+ Power)	0	-76	65	-80
S3 (+Trans)	0	-80	31	-80
S4 (+ En Eff)	0	-80	0	-80
S5 (+ Hhold)	0	-80	0	-80

In S2, where additional regulations and market-based incentives are added to the power sector, China and Taiwan are able to meet their emissions reductions targets. Japan and Korea are not, however, mainly due to high emissions levels in transport and industry. Once further policies are added to the transport sector (S3), Japan is able to meet its emissions reduction target (albeit with a high carbon price, see below) but Korea is still not able to. Only once the energy efficiency policies are added in S4 does it become possible for all countries to meet their emission reduction targets.

Table 4 CO_2 prices in each scenario, 2050

(2018 prices, \$/tCO_2, additional to baseline)

	China	Japan	Korea	Taiwan
Baseline	0	0	0	0
S1 (C Tax)	1,500	1,500	1,500	1,500
S2 (+ Power)	717	1,500	1,500	750
S3 (+Trans)	101	1,050	1,500	750
S4 (+ En Eff)	43	321	390	525
S5 (+ Hhold)	21	293	218	420

Table 4 shows the carbon prices in each scenario. In cases where the carbon reduction targets are not met, a maximum value of \$1,500/tCO_2 is applied. In all the scenarios, a path of linear increases is applied over the projection period. The table shows the role that non-pricing policies can play in reducing overall emissions levels. The case is clearest in China, where without additional policies, a carbon tax set at the maximum rate would not bring emissions back down to 1990 levels. When other

policies are added, however, a very modest carbon tax rate is required to meet the target. The findings in part reflect the large share of Chinese emissions from coal-fired power plants and the potential to replace these plants with renewables.

In the other countries a large carbon tax (by today's standards) is required to meet the emissions reduction targets. Each of the countries faces its own challenges. Japan has little scope to reduce power sector emissions and may see increases in emissions from the sector, depending on nuclear policy. Korea has a large and growing energy-intensive industrial sector. In the case of Taiwan, we have set a very ambitious target to reduce emissions.

All four countries must also find ways to reduce emissions from road transport. Carbon taxes are often ineffective in road transport because motor fuels are already taxed highly and motorists do not have many alternative options. If incentives to encourage adoption of electric vehicles (including subsides and infrastructure development) are put in place, then there is much more potential for carbon taxes to work (i.e. there is a strong policy interaction). Transitions take time, however, and there is also a role for biofuels to replace current liquid fuels.

It should also be noted that there is a strong role for energy efficiency in these scenarios. Regulatory measures can cover low rates of uptake in energy efficiency products that are due to factors such as knowledge gaps or misaligned incentives. Without these measures, some of the easiest ways to reduce emissions may not be taken up.

4.2 Impacts on the economy

Table 5 shows the impact of the different policies on GDP in each country. It should be noted that the national policies are implemented simultaneously and so trade effects between the different countries are included in the impacts. For example, if GDP increases in China there can be a boost to demand for exports from the other countries in East Asia.

It should also be noted that we have not included any revenue recycling measures in the analysis. The revenues from the carbon taxes are used to pay down government debt, rather than boosting demand elsewhere in the economy. Some of the other measures require government expenditure, however, notably the energy efficiency investments; and therefore provide an economic stimulus.

We plan to extend this work to include versions of the scenarios in which government balances are fixed to zero through a revenue recycling mechanism. It is noted, however, that the type of recycling mechanism used can have a strong impact on the model results (Park et al, 2016); a double dividend is possible but the choice of recycling method can have as much impact on results as the carbon tax itself.

Table 6 shows the changes in government balances by 2050. These numbers are calculated from carbon tax revenues minus climate policy costs introduced in the scenarios. The climate policy costs included in the calculation are funding for energy efficiency investment, subsidies for new technologies and scrappage costs. It should be noted that the government subsidies occur in the early years and are phased out by 2050, so the remaining expenditure is for energy efficiency investment. There are also changes in government balances as a result of changing economic activities that are not reported here.

The results show that the carbon tax alone could raise up to 28% of national GDP in S1, which highlights that a rate of $1,500/tCO2 without other policy is rather unrealistic. Since there is no revenue recycling, these additional revenues are used to improve the government balance. However, the results for other scenarios also show that all the climate policies introduced in our scenarios can be more or less self-funded if combined with the carbon tax. Some readers may be surprised to see positive GDP impacts, for example in three of the four countries in S5. In part, the positive impacts are due to the stimulus from government expenditure but there may also be a private sector stimulus from additional investment in energy efficiency and renewable equipment. Finally, in all the scenarios there is a reduction in imported fossil fuels; a shift from spending on imports to spending on domestically-produced goods could give a further stimulus effect.

Table 5 Impacts on GDP, % from baseline in 2050

	China	Japan	Korea	Taiwan
S1 (C Tax)	-0.7	-4.3	-1.6	-3.9
S2 (+ Power)	-0.6	-4.1	-1.2	-1.8
S3 (+Trans)	-0.1	-3.2	-0.8	-1.5
S4 (+ En Eff)	0.3	0.8	0.8	-1.2
S5 (+ Hhold)	0.3	1.0	1.0	-1.0

Table 6 Change in govt balance*, % of GDP from baseline in 2050

	China	Japan	Korea	Taiwan
S1 (C Tax)	14%	9%	18%	28%
S2 (+ Power)	4%	5%	13%	4%
S3 (+Trans)	0%	3%	11%	4%
S4 (+ En Eff)	0%	1%	2%	3%
S5 (+ Hhold)	-1%	1%	1%	2%

Note(s): * only cover carbon tax revenues minus climate policy costs only. Climate policy costs include funding for energy efficiency investment, FTT subsidies and scrappage costs.

It is notable that the magnitude of the GDP impacts varies substantially between the different countries. Japan and Taiwan see much larger losses of GDP than China and Korea. This is despite China and Korea remaining more carbon intensive in production by 2050 than Japan and Taiwan (in both cases by 2.5-3 times).

The reasons for this finding vary between the countries. In China, what happens to energy prices is important. China has such a large weight in global energy consumption that its policies impact on global prices. So, while CO_2 prices increase the costs of production, falling coal and fuel prices (13% and 9%, respectively) offset higher costs to some extent. Although electricity prices increase by almost 50%, parts

of Chinese industry are unable to pass on higher prices due to global competition. Domestic action in China therefore has a more limited impact on the prices faced by Chinese consumers.

In Korea, there is a large increase in prices, but this increase is matched by wage growth. While higher wages rates and unit costs have some negative competitiveness effects (although mitigated here because the rest of the world is also implementing climate measures), the loss of real incomes is reduced. In previous analysis with the E3ME model (Park et al, 2016), we have found that in Japan, wages have tended to be rigid, although it should be noted that the econometric equations are based on time series that cover a long period of deflation in Japan.

Table 7 shows the impacts across the different economic sectors (aggregated from the 42 sectors in E3ME). The largest falls are in the sectors that are associated with energy and they are fairly consistent across scenarios (less in S1 because the carbon reduction targets are not met). Within the other sectors, there is a general improvement as the carbon price is reduced, in line with the aggregate GDP impacts. Construction and advanced manufacturing (including engineering) could gain the most from the additional investment.

Table 7 Impacts on sectoral output, % from baseline in 2050 (East Asia)

	S1	S2	S3	S4	S5
Agriculture	-2.0	-1.6	-1.4	-0.5	-0.3
Basic manu.	-1.1	-0.9	-0.1	0.5	0.5
Advanced manu.	-1.0	-0.8	0.2	0.9	1.0
Energy extraction	-53.1	-60.7	-61.8	-59.8	-60.1
Utilities	-6.3	-3.8	-11.2	-10.3	-10.0
Construction	0.5	-0.1	2.1	2.6	2.6
Services	-1.6	-1.3	-0.9	-0.1	0.1

Table 8 Impacts on employment, % from baseline in 2050

	China	Japan	Korea	Taiwan
S1 (C Tax)	-0.8	-1.7	-2.1	-1.0
S2 (+ Power)	-0.5	-1.7	-2.0	-0.4
S3 (+Trans)	-0.3	-1.5	-2.0	-0.4
S4 (+ En Eff)	0.0	0.2	0.0	-0.4
S5 (+ Hhold)	0.0	0.3	0.3	-0.4

The results for employment to some extent follow from the GDP impacts (see Table 8). As a general rule of thumb (Okun's Law), the impacts on employment are half the

size of the impacts on GDP. In the cases of Japan and Taiwan, this is roughly what we observe (in both cases the ratios are a bit less than half). In China the impacts on employment may be larger than aggregate GDP impacts. This finding is not new and reflects the large numbers of jobs that are likely to be lost in the Chinese coal sector. As the amount of value added per job is relatively low in the coal sector, it is possible at aggregate level to see larger impacts on employment than on GDP. In Korea, the same reaction in wages that reduces GDP costs leads to a larger reduction in employment. These results show how important it is to consider labour market responses in this type of analysis.

5 Conclusions

Mainstream neoclassical economics suggests that the 'optimal' way to reduce carbon dioxide emissions is to put a tax on them. The carbon tax provides a price signal that can incentivise households and businesses to adapt their behaviour accordingly. Under this theory, any other policies that try to reduce emissions will lead to a misallocation of resources and sub-optimal outcomes.

In the world that policy makers face, however, many of the assumptions that underpin neoclassical economics do not hold. Agents do not have perfect knowledge or foresight and may not act in a fully rational manner. Market prices may not be able to adjust instantly to balance supply and demand, and carbon prices alone may not provide incentives to develop the technologies that are necessary to reach long-term decarbonisation goals. Furthermore, there may be strong political resistance to a carbon tax with a high rate, for example due to competitiveness or energy poverty issues.

To understand the impacts of implementing a broader range of policies, policy makers need modelling tools that can represent these policies within a broader, simulation-based framework. In this paper we have applied such a framework, using the E3ME macro-econometric model linked to FTT bottom-up sub-models of the power, passenger transport and household heating sectors.

We test five scenarios (S1-5) that include carbon prices and a set of policies that expands as we progress. The policies that we have assessed cover the three 'pillars' that are described in Grubb (2014). Specifically, we address short-term easy wins through mandating energy efficiency standards across the economy in S4. Policies to support the long-term development of new technologies are added in S2, S3 and S5. The carbon price ensures that there is sufficient incentive for new technologies to be adopted, once gaps in knowledge are considered.

For each of the four East Asian countries we have set ambitious decarbonisation targets. Our scenarios show that carbon prices alone (S1) will not be sufficient to meet the targets, unless the carbon prices were to be unrealistically high (above \$1,500/tCO_2 in 2018 prices). As we add policies to the power, industrial, road transport and household sectors, not only do the emissions reduction targets become attainable, but the carbon price required to do so becomes less. From a price of \$1,500/tCO_2 that fails to reach the targets, we find a range of \$21-420/tCO_2 in S5 that are in line with the targets.

The economic impacts of the carbon taxes are also reduced when a lower rate is applied. We do not apply revenue recycling in this analysis, so the carbon tax rates on their own are a burden to the East Asian economies. Reducing the tax rates allow

some of the more positive impacts, for example through reduced fuel imports or investment stimulus, to play a larger role in the results. We find similar patterns in our results for employment.

Further discussion of the economic results requires a version of these scenarios that includes revenue recycling, for example through reducing income tax rates or sales tax rates with the revenues from the carbon tax (net of any public investment costs). However, it is clear that a lower carbon tax rate would reduce distributional impacts across sectors and therefore improve the political feasibility of the overall policy package. To summarise, this is the sort of analysis that policy makers are increasingly going to require as the world moves from setting emission reduction targets to asking how to meet the targets that have been set. We hope that our analysis provides a first step in this process.

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