

Economic Impacts of Future Changes in the Energy System—Global Perspectives

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Abstract In a climate constrained future, hybrid energy-economy model coupling gives additional insight into interregional competition, trade, industrial delocalisation and overall macroeconomic consequences of decarbonising the energy system. Decarbonising the energy system is critical in mitigating climate change. This chapter summarises modelling methodologies developed in the ETSAP community

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to assess economic impacts of decarbonising energy systems at a global level. The next chapter of this book focuses on a national perspective. The range of economic impacts is regionally dependent upon the stage of economic development, the level of industrialisation, energy intensity of exports, and competition effects due to rates of relative decarbonisation. Developed nation's decarbonisation targets are estimated to result in a manageable GDP loss in the region of 2 % by 2050. Energy intensive export driven developing countries such as China and India, and fossil fuel exporting nations can expect significantly higher GDP loss of up to 5 % GDP per year by mid-century.

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1 Introduction

1.1 Why Link Energy-Economy Models?

In these two chapters the current state of the art of methods within the ETSAP community to couple energy systems models to macroeconomic models are presented. This chapter covers perspectives on the environmental rationale, model coupling development, outlines model coupling policy and research applications at the global and regional level. Next chapter of this book continues with national case studies, showing the UK's legislative use the coupled hybrid MARKAL¹-MACRO (MM) model, and updates to the mathematical formulations of its successors TIMES²-MACRO (TM) and most recently TIMES MACRO-Stand-Alone (TMSA). The energy systems models discussed are bottom-up (BU) techno-economic linear optimisation engineering TIMES models, while coupled to top-down (TD) macroeconomic models. These range from single producer-consumer agent production function models, to multi-region structural computable general equilibrium (CGE) models. Both chapters collate the collective work that was presented at an IEA-ETSAP funded workshop in University College Cork in February 2014. They conclude synthesising common critical messages from the range of studies. The applied theory of what constitutes a consistent, pragmatic and heuristic model linkage is discussed. Soft-linking and hard-linking multi-model methods are introduced with attention paid to model structures, consequent data harmonisation and data transfer frameworks. Multi-regional models add insight into trade and competition effects upon delocalisation. Overall, maintaining a consistent paradigm throughout model coupling is critical in understanding the economic impacts of future changes to the energy system.

Affordable access to an acceptable energy supply is critical for a prosperous stable economy. Functional markets are theorised to price primary energy supply commodities, their refined products and final consumer energy products. Non market externalities such as green-house-gas (GHG) emissions or long term strategic policy decisions are difficult to fully include in near term commodity futures pricing, as a result of changing trends and resultant uncertainty. Half of all cumulative anthropogenic CO₂ emissions have occurred in the past 40 years. Increasing energy system carbon intensity between 2000–2010 has contributed to GHG growth increasing to 2.2 %/year when compared with 1.3 %/year over the previous three decades (IPCC 2014). Two thirds of global GHG emissions are produced by the energy system. The energy system analysis of International Energy Agency's (IEA) New Policy Scenario leaves the world on track for a long term average temperature increase of 3.6 °C, dangerously beyond the 2 °C limit (IPCC 2013; OECD/IEA 2013). A restructured low-carbon world economy is thus imperative (Capros et al. 2014; Krey et al. 2014).

¹ MARKAL—MARKet ALocation model.

² TIMES—The Integrated MARKAL-Efom System.

Internalising the energy system GHG environmental externality by appropriate pricing mechanisms via emissions permits trading markets and carbon taxation is seen as the primary means to drive decarbonisation in the energy system. In energy systems modelling, the marginal abatement cost of carbon is typically used as the scenario comparison yard-stick. Carbon pricing is critical to stabilise investor expectation to promote investment in marginal mitigation technologies. The European emissions trading scheme (EU-ETS) has made efforts to account for the environmental externality, but thus far has failed to be the causal force in reducing carbon emissions. It must be fixed, and other regions must similarly collaborate (Edenhofer 2014). Otherwise, climate change—essentially a commons problem—could become the modern era “tragedy of the commons” (Hardin 1968; Nordhaus 1994). Recently the UK has made efforts to correct this market failure with amending policy to introduce a carbon price floor (HM Revenue and Customs 2013). Revenue recycling schemes from carbon taxation can bring long term decarbonisation benefits to near term social good, tacking climate inequality, or achieve revenue neutrality. Policy-makers need tools to understand the effectiveness and the economic impact of policies whose purpose is to shift energy systems toward more environmentally desirable development pathways (Hourcade et al. 2006). Understanding energy-economy coupling is crucial in analysing regional effects of carbon tax, trade, competitiveness, and energy policy at large.

Accounting the cost of investment required to achieve least cost energy systems is achievable with technology rich BU energy systems models. The rationale behind linking engineering energy systems models with macroeconomic models is to include the feedback effect between energy cost and energy service demands. Coupling energy-economy models enables analysis of heterogeneous sectoral dynamics while providing a more suitable microeconomic framework (Bataille et al. 2006), that energy systems models on their own can only approximate with elastic demand. The objective is to estimate the changes in welfare and growth, where deviation from business-as-usual (BAU) in investment requirements induces productivity and consumption pattern changes through substitution effects. The potential magnitude of these effects vary considerably across differing economic schools of thought; from neoclassical to ecological economics; from growth opportunities to deep sustainability (Warr and Ayres 2006; Strachan and Kannan 2008; Jackson 2009; Ayres et al. 2013; Krey et al. 2014; The Global Commission on the Economy and Climate 2014). GHG emissions are typically the constraint driving redistribution of investment capital causing macroeconomic feedback, but of course this is not the only model scenario that could be considered. The macroeconomic cost of energy supply insecurity is an alternate use of model coupling, as is energy export and trade dynamics. The benefit of soft-linking energy system and macroeconomic models is in utilising the complementary strengths of both models to overcome the other’s weaknesses. This allows additional insights of technological and economic detail to be gleaned that otherwise would not be quantified.

1.2 BU and TD Models

BU engineering models and TD macroeconomic models have evolved as the economically consistent means of assessing long term energy system dynamics and costs (Wene 1996; Hourcade et al. 2006). BU models include *optimisation, simulation, accounting and multi agent techniques* (Fleiter et al. 2011). Some TD methods include *input–output, econometric, computable general equilibrium* (CGE) and *system dynamic models*. This chapter is primarily focused on coupling TIMES optimisation and CGE models.

BU model methods are explicit in their data richness and outline detailed technology development pathways, interdependencies and costs. TIMES and its forebear MARKAL form the primary constituent parts of a family of linear programming models supported by ETSAP under an implementing agreement of the IEA. TIMES is a techno-economic model generator for local, national or multi-regional energy systems, which provides a technology rich basis for estimating energy dynamics over a long-term (20–50 years), multi-period time horizon. TIMES computes a time varying inter-temporal partial equilibrium on inter-regional markets. The objective function maximises total surplus. This is equivalent to minimising the discounted total energy system cost while respecting environmental, technical and scenario constraints. This system cost includes investment, operation and maintenance and fuel import costs, less export income, terminal technology values and salvage values. This approach does not consider the same microeconomic theoretical underpinnings as a TD model and can be viewed as the optimisation by a clairvoyant energy planner with perfect information and perfect foresight over the total system, rather than maximising consumer choice preferences at a microeconomic level. Thus, TIMES models reference scenario pathways are driven by energy service demands exogenously defined by macroeconomic conditions and resource supply curves; while, subsequent dynamics are driven by environmental constraints under user consideration. The technical foundations of MARKAL is outlined by Fishbone and Abilock, while the full technical TIMES documentation is hosted online by ETSAP (Fishbone and Abilock 1981; Loulou et al. 2005).

TD CGE methods describe the whole economy, mapping and subdividing sectoral structures where substitution between factors of production is allowed. CGE models are built upon microeconomic theory to calculate prices and activities in all sectors of an economy to reach a general equilibrium. Consumers maximise their utility through demanding goods met by producers who maximise profits (Arrow and Debreu 1954; Johansen 1960). Historical national or global accounts data is required for calibration, where the Global Trade Analysis Project (GTAP) database is the most commonly used example. TD models in general, namely CGE models, do not include many technical aspects of the energy system. The energy system combined with the other factors of production, forms of capital and labour, are described in inter-related production functions to optimise consumer utility and economic growth. Capital value shares, elasticities of substitution, and autonomous

energy efficiency improvement coefficients—estimating technological learning—and marginal technology cost curves (Kiuila and Rutherford 2013) enable estimation of technology choice and fuel switching dynamics.

The Lucas critique argues econometric models based on historic trends cannot model policy changes nor remain valid in future technology paradigm shifts (Lucas Jr 1976; Grubb et al. 2002). CGE models usually have smooth rates substitution, whereas poorly constructed optimisation models can display a “flip-flop” binary characteristic related to the capacity size of the marginal technology choices and level of model constraints (Grubler et al. 1999). The different approaches can provide differing solutions and result in differing policy conclusions. However, CGE models can give long term macroeconomic outlooks to drive TIMES energy systems models which can in-turn feedback energy costs adjustments to the CGE model, which upon iteration provides new energy demands (Hoffman and Jorgenson 1977). In a consistent framework the coupled hybrid model can build a more accurate representation of the system under scrutiny.

1.3 Hybrid Model Evolution

The linking of the Brookhaven Energy System Optimisation model (BESOM) with a CGE model is the first hybrid energy-economy model reported (Hoffman and Jorgenson 1977). The outputs of each of the individual models were transferred between each other manually by the user, in what has become known in the proceeding decades as *soft-linking*. Soft-linking is typically the simplest starting point by its transparency, flexibility, learning (Martinsen 2011), and practicality in establishing consistent common measuring points (CMP) in the overlap of model structures.

The alternative of programmatically linking of models to automate data transfer between models is known as *hard-linking*. MARKAL-MACRO is the first such reported hard-linked energy-economy model (Manne and Wene 1992), and is the basis for the subsequent TIMES-MACRO, TIMES-MSA and others (Manne et al. 1995; Wene 1996; Messner and Schrattenholzer 2000). Hard-linked models tend to establish optimum data transfer methods, enabling greater productivity, control, convergence and solution uniqueness. Historically hard-linking has come at a computational cost, requiring the model to be a reduced form single sector model (Manne and Wene 1992; Manne et al. 1995; Böhringer 1998; Messner and Schrattenholzer 2000; Bosetti et al. 2006; Strachan and Kannan 2008). This results in aggregated energy economy interactions, giving overall trends but limits its usefulness when applied to sector specific enquiries.

Combining BU and TD models in a mixed complementarity problem introduces a limited set of technological sectoral detail into a CGE framework (Frei et al. 2003; Sue Wing 2008; Proença and St. Aubyn 2013). The whole energy system cost optimisation problem could be integrated into a CGE model, with decomposition to improve solution algorithm performance and reduce computation time (Böhringer 1998; Böhringer and Rutherford 2008, 2009). However, the authors are not aware

of such a model. Aside, the International Monetary Fund have made attempts to integrate oil supply dynamics into their global dynamic stochastic general equilibrium model GIMF (Benes et al. 2012; Kumhof and Muir 2014).

2 Linkage of the Global Energy Models TIAM-WORLD and GEMINI-E3

In order to assess climate mitigation agreements, an iterative procedure linking TIAM-WORLD and GEMINI-E3 is the first method proposed. TIAM-WORLD (TIMES Integrated Assessment Model) is a BU global multi-regional technology-rich optimisation model. GEMINI-E3 is a TD global multi-regional general equilibrium model (Loulou and Labriet 2008; Bernard and Vielle 2008). Recent work soft-linking the two models explores global and partial climate agreements (Labriet et al. 2015). An accurate representation of the energy and technology choices, and the macro-economic impacts, especially in terms of trade effects of climate policies, is critical in understanding future pathways to a climate constrained world.

TIAM-WORLD is part of the TIMES family of energy models and calculates a dynamic inter-temporal partial equilibrium on worldwide energy and emissions markets based on maximisation of total surplus (Loulou 2008). The version of the model uses in this application divides the world in 15 regions, driven by 42 energy service demands across all sectors. It covers the procurement, transformation, trade and end use of all energy forms, represented by over 1500 energy technologies and one hundred commodities in each region. Energy demands are calibrated by the user for the reference scenario, and each has its own price elasticity. Environmental emissions are endogenously modelled at the technology level. TIAM-WORLD integrates a climate module for the modelling of greenhouse gas concentrations, radiative forcing and temperature increase.

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium model. It represents the world economy in 28 regions and 18 sectors. The standard model is based on the assumption of total flexibility on both macroeconomic markets, such as the capital and the exchange markets (the associated price are the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production). GEMINI-E3 is calibrated with the GTAP database which includes physical energy market data, social accounting matrices and bilateral trade flows.

2.1 Data Harmonisation

The initial harmonisation of the two very different model structures represents a critical challenge for hybrid model's theoretical consistency. Each of the model regions and commodities need to be paired. Furthermore, reference scenarios

require harmonisation of the basic drivers of the energy system, being population growth, GDP trends, energy prices and energy policy constraints. Once harmonized, the reference cases of TIAM-WORLD and GEMINI-E3 propose similar CO₂ emission trajectory until 2030. Differing technological assumptions lead to longer term divergence of CO₂ trajectories. This effect has also been seen in similar modelling exercises (Labriet et al. 2012; Kanudia et al. 2014; Krey et al. 2014).

2.2 *The Coupling Method*

The purpose of the linkage of the models is to allow the strengths of each model (technological richness of TIAM-WORLD and macro-economic details of GEMINI-E3) to augment the overall analysis of energy and climate policies. The coupling approach optimises the data flow of common market points, from the model of relative more accuracy, to the other model. GEMINI-E3 receives data from TIAM-WORLD on energy and CO₂ prices, technical progress on energy use and capital consumption. TIAM-WORLD receives sector economic production data to recalculate energy service demands.

TIAM-WORLD only goes through one major modification: the removal of price elasticities of the energy service demands. This microeconomic behaviour is modelled by GEMINI-E3. GEMINI-E3 requires more numerous modifications to consistently utilise the data linkages: energy technologies that are not present in the standard version of GEMINI-E3, such as biomass, hydrogen, nuclear and other renewable energy sources are added to the model structure and the nested structure of the CES functions are rewritten; the CES functions relating to all energy consumption are replaced by Leontief function, whose coefficients representing the energy shares are computed on the basis of TIAM-WORLD results; technical progress is modified with energy efficiency improvements from TIAM-WORLD; finally, energy and carbon prices are computed by TIAM-WORLD.

The coupling procedure is carried out in a Gauss-Seidel method (Hageman and Young 2012) which seeks a fixed point for the useful demand vector through an iterative process. TIAM-WORLD is first run with useful demands from the harmonisation phase of the two models. TIAM-WORLD passes its results to GEMINI-E3, which is re-run. This is the first iteration. New macroeconomic output and industrial value added obtained from GEMINI-E3 are used to re-estimate the energy service demands. This process is repeated until model convergence is reached, defined as the Euclidean distance between the two last demand vectors over the norm of the last demand. Convergence is typically achieved in 6 iterations for climate constrained scenarios.

2.3 Results

Both global and partial climate agreements are studied with the proposed coupling methodology.

The comparison of the Iron and Steel production results obtained with TIAM-WORLD in a standalone manner with elastic demand and with the coupled models illustrates one of the added-value of the coupling: in a global climate agreement, while the iron-and-steel production decreases in all countries in TIAM-WORLD used in a standalone manner, several countries increase their production in the coupled models to compensate the production decrease in China and India. The combined analysis of trade, provided by GEMINI-E3, and energy dynamics, provided by TIAM-WORLD, helps understand these decisions: India and China prefer importing Iron and Steel from some other countries rather than producing it locally with clean energy and processes because of the lack of clean production opportunities in these countries compared with the others, more particularly biomass-fired power plants opportunities with carbon capture and sequestration.

However, the differences in sectoral emissions between TIAM-WORLD used in a standalone manner and the coupled models are smaller than 5 % over the model time horizon. This is an interesting result, showing that the inter-sectoral effects of climate policies have little effect on overall aggregated sectoral emissions.

In partial agreements, the coupled models help the assessment of the delocalisation of not only primary energy extraction (to Former Soviet Union and Africa), represented in TIAM-WORLD but also industrial production (to Asia), provided by GEMINI-E3. However, emission leakage remains small, mainly due to global lower oil demand.

The macroeconomic analysis from the coupled models also shows fossil fuel exporting countries, represented by the Middle East, Former Soviet Union and to a lesser degree Africa, are all extremely penalized by climate constraints. This simply occurs as a result of trade imbalances consequent to energy export revenue reductions while fossil fuel production declines.

2.4 Discussion

The two global models are coupled through an iterative exchange of data until convergence of energy demands. It builds upon the technology richness of TIAM-WORLD and the macro-economic details of GEMINI-E3. Technology changes, macroeconomic and inter-sectoral effects are assessed with the coupled models.

Although such an approach minimizes the number of structural changes of the original models compared to the full integration of models within a same optimization framework (Labriet et al. 2015), a meticulous examination and understanding of both models is crucial in order to define the correspondence between energy commodities, regions, economy sectors, to build the data exchanges

between both models, and to avoid any methodological inconsistencies (Böhringer and Rutherford 2009).

An added value of the proposed coupling framework at a global scale is the understanding of the energy system transition interdependences upon trade and competition effects.

3 Global Energy Policies Analysed with TIAM-FR and IMACLIM-R

The hybrid linking of TIAM-FR and IMACLIM-R, while conceptually similar to linking TIAM-WORLD and GEMINI-E3 (summarised in Sect. 2), is fundamentally different in a specific assumption of perfect foresight. The CGE model IMACLIM-R allows the exploration of the differences in myopic technology pathways due to recursive time dynamics, i.e., the model is solved in sequential (yearly) time steps, linked through time by capital accumulation based on exogenous savings rates, while TIAM has perfect foresight of technology availability and development. This first section focuses on the reconciliation of these theoretical differences.

TIAM-FR, a version of the TIMES Integrate Assessment Model (TIAM) developed in France, is a typical BU TIMES model that has been widely used to assess sectoral and global energy and climate policy from both developed and developing countries perspective (Bouckaert et al. 2011; Assoumou and Maïzi 2011; Ricci and Selosse 2013). IMACLIM-R, is the recursive version of IMACLIM, a multi-regional multi-sector TD model that has been developed by CIRED to assess the long-term global economic impacts of climate policy (Guivarch et al. 2009; Sassi et al. 2010; Mathy and Guivarch 2010; Rozenberg et al. 2010; HAMDI-CHERIF et al. 2011).

The divergent viewpoints of models developed by energy engineers, or BU models, and those developed by economists, or TD models, can hinder effective dialogue and mutual understanding between researchers from different academic backgrounds. The purpose of this work is to promote a constructive dialogue between modellers from each side of the modelling paradigms, based on a comparative critique of the BU TIAM-FR model and the TD IMACLIM-R model.

3.1 Method

First and foremost, the conceptual frameworks (optimisation *vs.* recursive) of the two models must somehow be reconciled, and is done so with approaches to harmonise the theoretical structure, data and nomenclature of each model.

TIAM-FR is geographically aggregated in 15 world regions. It covers the time horizon from 2005 to 2100 to properly reflect the long-term nature of the climate

constraint. Indeed, a climate module computes the change in CO₂ concentrations in atmospheric radiative forcing from anthropogenic activities and the temperature change relative to the pre-industrial period. The climate module does not induce retroactive energy services demands, which remain unchanged. More generally, TIAM-FR is driven by 42 exogenous end-use energy demands grouped into six sectors. Each energy demand is calibrated for the base year, and then follows a trend induced by some exogenous driver, *i.e.* regional economic and demographic projections and region-specific elasticities.

IMACLIM-R provides a more aggregated view of global economic activity, which it divides into 12 regions and 12 sectors. The base year of the model (2001) builds on the GTAP-6 database, a balanced Social Accounting Matrix (SAM) of the world economy although the original GTAP-6 dataset was modified to (i) aggregate regions and sectors according to the IMACLIM-R mapping, and (ii) accommodate the 2001 IEA energy balances (Sassi et al. 2010; Rozenberg et al. 2010).

IMACLIM-R's rationale stems from the necessity to understand better, amongst the drivers of energy-economy prospective trajectories, the relative role of (i) technical parameters, (ii) structural changes in the final demand for goods and services (dematerialisation of growth patterns) and, (iii) micro and macroeconomic behavioural parameters in open economies. This is indeed critical to capturing the mechanisms in the transformation of a given environmental alteration into an economic cost and in the widening or narrowing margins of freedom for climate mitigation or adaptation.

To fully exploit the potential of this dual representation requires abandoning the use of conventional aggregate production functions, which roughly represents the technological constraints impinging on an economy (Berndt and Wood 1975) and (Jorgenson 1982). It is indeed arguably impossible to find mathematical functions flexible enough to encompass all the contrasted scenarios resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade 1993), for small as well as for large departures from the reference equilibrium. This accounts for the already reported absence of formal production functions in IMACLIM-R.

IMACLIM-R and TIAM-FR use the same data and scenario with regards to the growth of population, from the United Nations. The global geographical division in TIAM-FR have been reprocessed from the simulation outcome of IMACLIM-R and re-aggregated in accordance with its 15 regions. The macroeconomic indicators were integrated into the TIAM-FR model to drive the energy service demand and, from it, determine the energy system in an optimisation framework. TIAM-FR model is then re-run with the macroeconomic output indices coming from IMACLIM-R to calculate the optimal outcome of the energy supply system and carbon emissions trajectories at the world level

Three Scenarios are considered, a business as usual scenario (BAU), and two climate scenarios (CLIM), one with BAU drivers, *Clim_dBAU* and the third scenario with drivers from a climate run of IMACLIM-R, *Clim_dClim*. More precisely,

BAU scenario from TIAM-FR is based on macroeconomic indicators extracted from the BAU scenario of IMACLIM-R. Concerning the climate scenario, CLIM_dBAU and CLIM_dCLIM refers to two different trajectories consistent with the 450 ppm target in 2100 for CO₂ emissions. CLIM_dBAU is derived from simulation based on the BAU growth indices in IMACLIM-R, whereas CLIM_dCLIM is driven by growth indices from the 450 ppm scenario in IMACLIM-R. The price elastic energy demand functions are not used in running TIAM-FR as the prices have not been harmonized between the two models.

3.2 Results

The results specifics are not in focus here but more so the relative impact between scenarios are of interest in investigating the demand reduction as a result of climate scenario in IMACLIM-R. CO₂ emissions paths induced by climate constraints are reported in Fig. 1.

The comparison of CLIM_dBAU and CLIM_dCLIM pathway shapes illustrates again the divergence between TIAM-FR and IMACLIM-R in terms of modelling philosophy. Under an inter-temporal optimized abatement trajectory (CLIM_dBAU), emissions may keep growing by 2040 then slightly drop until 2060 before declining sharply. By contrast, the agent cannot see this *optimal* abatement pathway in the IMACLIM-r. Therefore, the pricing signal must be very strong, to reflect the 450 ppm constraint to curtail the fossil-fuel dependent goods and services demand. The growth indices would be much lower than in the case of the *optimal* growth in the short and mid-term. However, in the long run, there would be more flexibility for emission growth in CLIM-dCLIM than CLIM_dBAU as the economy will be largely decarbonized and thus offers more room for an emissions increase. TIAM-FR and IMACLIM-R suggest different timing and arbitrage for sectoral emission abatement for a given climate target (Fig. 2).

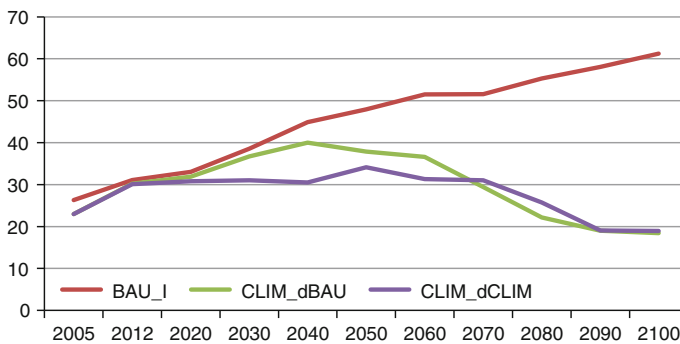


Fig. 1 World CO₂ emission trajectories under the three example scenarios (Gt)

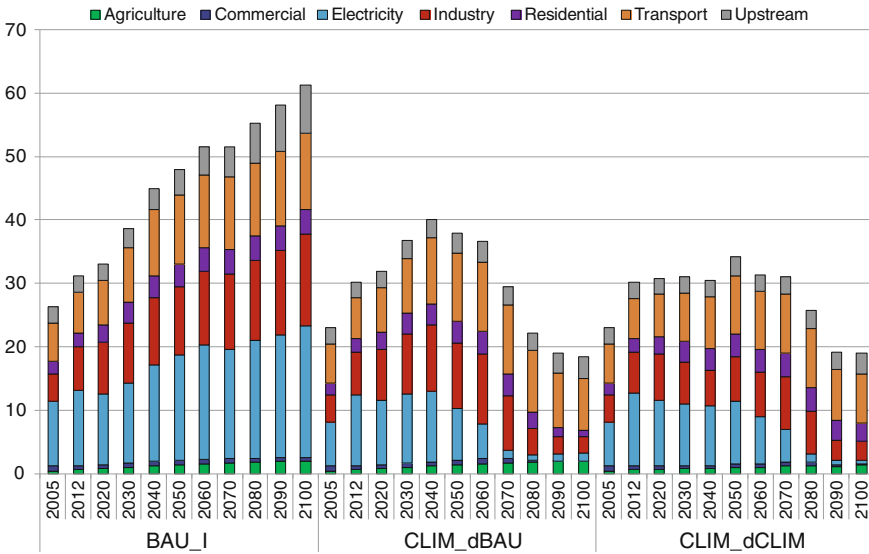


Fig. 2 World CO₂ emissions by sector (Gt)

In the CLIM_dBAU scenario, the CO₂ emitted by the electricity sector decreases from around 7 Gt in 2005 to 1.2 Gt in 2100. CO₂ emissions reach 0.6 Gt in 2100 in the CLIM_dCLIM scenario. CO₂ emissions represent nearly 21 Gt in 2100 in the BAU. The electricity sector share of total CO₂ emissions moves from 30 % in 2005 to 7 and 3 % respectively in CLIM_dBAU and CLIM_dCLIM. While CLIM_dCLIM appears more stringent in terms of decarbonisation for the electricity sector, it is interesting to note that the CO₂ emissions mitigation in the industry is more important in CLIM_dBAU than in CLIM_dCLIM with 2.6 Gt of CO₂ emitted in 2100 in the former against 3 Gt of CO₂ emitted in the latter scenario. CO₂ emissions in industry in 2100 represent 14 % in CLIM_dBAU and 16 % in CLIM_dCLIM of the total CO₂ emissions (24 % in BAU) against 19 % in 2005.

Other sectors impacted by the climate policies implemented in scenario are commercial and residential. In the BAU, these sectors account for 1 and 6 % respectively of the CO₂ emissions in 2100 (3 and 7 % in 2005). In CLIM_dBAU, they represent near to zero and 5 % respectively for commercial and residential sectors in 2100 and 1 and 16 % respectively in CLIM_dCLIM at the same period. The CO₂ emissions in commercial sector move from 0.8 Gt in 2005 to 0.007 Gt in 2100 (0.1 Gt in CLIM_dCLIM and 0.5 Gt in BAU) in 2100. Note that in the BAU, the CO₂ emissions from the commercial sector are less in 2100 than in 2005. As regard the CO₂ emissions in residential sector, they reduce from 1.9 Gt in 2005 to 0.9 Gt in 2100 (2.8 Gt in CLIM_dCLIM and 3.9 Gt in BAU in 2100).

3.3 Discussion

This coupling tentatively shows that modellers can benefit from information on the whole economy with the representation of factor markets (capital, labour) from a Macro model on the one hand, combined with technology richness of the BU models, which represent better the technologies available in a specific bounded economy for a given time. Nevertheless, the models do not necessarily converge due to the difference in structural design and modelling paradigm. Some technical and mathematical challenges need to be addressed to provide insights into policy recommendations. The applied methodology presents some limitations in terms of indicators harmonization and prices consistency and results should be interpreted with care. From microeconomic point of view, a major difference residing in TD and BU models is that the behaviours of both energy suppliers and end-users may affect significantly the general equilibrium and underlying prices on the different markets; which in turn will have repercussions on the investment and savings decisions across regions. Also, the government's fiscal policies play a central role in boosting or slowing the economic growth and influence all the institutions of the market.

4 From Global Modelling to Country Analysis: Focus on China with ETSAP-TIAM and AIM

China's economy and energy system developed rapidly since the 1980s, followed by an increase in CO₂ emissions. Analysing pathways for China's future development and associated global issues relies on complex global modelling tools that incorporate sufficient sub-regional details of China. Recent modelling exercises that account for such global and sub-regional economy and energy system features are however rarely described in the peer-reviewed academic literature (Mischke and Karlsson 2014).

This China soft-linking case study aims to bridge this knowledge gap between existing global and China-specific scenario studies, which are currently carried out by different academic institutions with multiple modelling tools (Mischke and Karlsson 2014). One example of such a modelling exercise for China was carried out by Chen (2005). Using a hybrid MARKAL MACRO model for China, (Chen 2005) concluded that the economic costs of a carbon emission reduction pathway in China towards 2050 are rather high, estimated at up to 2.54 % of GDP loss.

The soft-linking of a global TD economic model, the Asian-Pacific Integrated assessment Model (AIM/CGE) developed in the National Institute of Environmental Studies of Japan (NIES), with a global BU energy system model, the ETSAP-TIAM model with sub-regional China features developed in the Technical University of Denmark (DTU), is carried out here to establish a common global and China-specific reference scenario. On this basis, global, China national and China

sub-regional economic, energy and emission pathways can be documented, analysed, and replicated simultaneously.

4.1 Methods

The two global optimization models are expanded with a sub-regional level of detail for China as per the country's regional geographic definitions of the 7th Five Year Plan (National People's Congress 1985). Both models represent the economy and energy system of 16 world regions plus China. China-specific base year data are calibrated against official Chinese government statistics, including provincial energy balances and input-output tables. The global AIM/CGE model represents moreover up to 30 provinces of China, with 22 economic sectors and three final demand sectors (Dai and Mischke 2014). A triangulation method to integrate provincial energy statistics for China into ETSAP-TIAM (Loulou and Labriet 2008) was established (Mischke 2013).

The soft-linking approach used in this study comprises the following three major steps, which are similar to other country case studies presented here:

Step 1: TD to BU

The AIM/CGE model provides initial inputs for the ETSAP-TIAM model for a direct or indirect linking of the sectors in both models. The outputs of the economic sectors from the AIM/CGE model are used as drivers for energy service demand in ETSAP-TIAM model. If required, alternative projections from other sources are used, such as population statistics.

Step 2: BU to TD

After ETSAP-TIAM calculates the optimal technology mix and final energy demand in different sectors, the energy efficiency parameters of the AIM/CGE model are adjusted so that the energy consumption matches the ETSAP-TIAM results.

Step 3: Model iterations

After these two steps, equivalent to the first iteration, the results of energy service demand in the AIM/CGE model might change. If the change in parameters is significant, new iterations are carried out until an acceptable convergence is found. The hybrid model developed in this study is named CGESL.

4.2 Common Reference Scenario

A common reference scenario is constructed and tested in various iterations. It follows the GDP and demographic trends of a newly developed, moderate Shared Socio-economic Pathways (SSP2) scenario (O'Neill et al. 2014). The SSP2

Table 1 Future economic growth increase for sub-regions of China under SSP2 (2005 = 1)

Region	2005	2010	2020	2030	2040	2050
East-China	1.0	1.5	3.5	6.5	9.8	12.3
Central-China	1.0	1.5	3.9	7.5	12.1	15.8
West-China	1.0	1.5	3.7	7.0	11.1	14.4

pathway is downscaled for China, following the principle that the existing socio-economic disparities within China will be narrowed towards 2050. Future GDP growth projections for China and other model regions are thus a main driver in both models. GDP pathways of East-, Central- and West-China are summarised in Table 1.

4.3 Reference Scenario Results

At a **global level**, the hybrid model (Fig. 1, marked in green) shows a 2–2.5 times increase in global power production, primary and final energy use and CO₂ emissions towards 2050. The pathway for final energy is thereby highly harmonised between the different modelling tools. The AIM/CGE model and the ETSAP-TIAM model (Fig. 3, marked in red and blue), if used stand-alone, diverge increasingly in their pathways for global power production, primary energy use and global CO₂ emissions.

At a **China national level**, the hybrid model (Fig. 4, marked in green) shows a 5 times increase in China's power production, primary and final energy use and CO₂ emissions towards 2050. A peak in these pathways is suggested around 2040 in the TD AIM/CGE and the hybrid CGESL model, however not in the BU ETSAP-TIAM model. As described above, the models stand-alone diverge increasingly towards 2050. While the TD AIM/CGE model calculates an almost 6 times increase

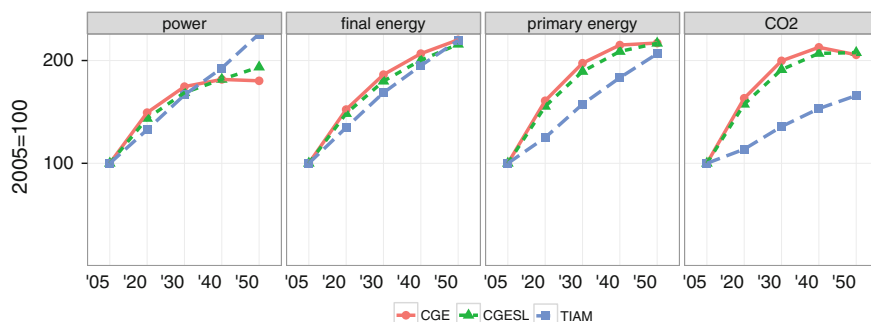


Fig. 3 World reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models—pathways for power generation, primary and final energy use, and CO₂ emissions towards 2050

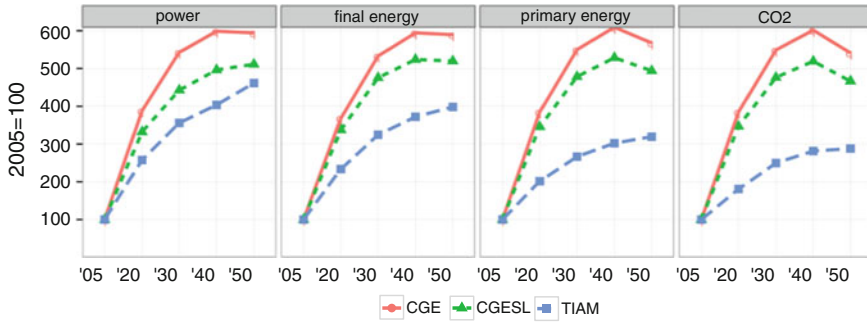


Fig. 4 China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models—pathways for power generation, primary and final energy use, and CO₂ emissions towards 2050

in all pathways towards 2050, the BU ETSAP-TIAM model calculates a much lower rate of increase of about 3–5 times.

Analyzing the modelling results for the **East-China sub-region**, which summarizes the highly developed coastal provinces of China, provides the further insights. The hybrid CGESL model (Fig. 5, marked in green) shows a 3.5–4 times increase in East-China’s power production, primary and final energy use and CO₂ emissions towards 2050. A peak around 2040 is suggested in most pathways studied here, similar to the national-level results for China. As discussed before, the models stand-alone diverge increasingly.

The pathways for the **Central-China sub-region**, which comprises many resource-rich provinces of China, are provided in Fig. 6. The hybrid CGESL model (Fig. 6, marked in green) indicates a 6–6.5 times increase in Central-China’s power production, primary and final energy use and CO₂ emissions towards 2050. The divergence in the pathways of the TD and BU models is highest for CO₂ emissions: the maximum increase in CO₂ emissions between 2005 and 2050 is about 7 times in the TD AIM/CGE model and only about 3 times in the BU ETSAP-TIAM model.

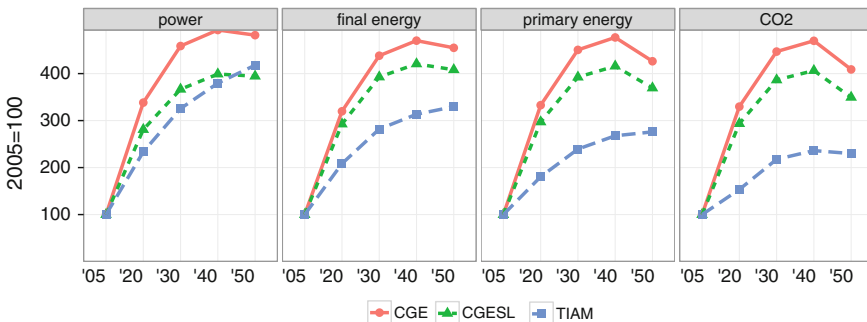


Fig. 5 East-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models—pathways for power generation, primary and final energy use, and CO₂ emissions (2005–2050)

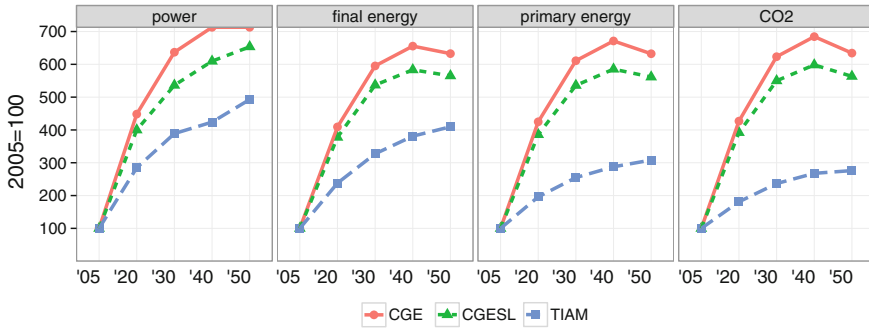


Fig. 6 Central-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models—pathways for power generation, primary and final energy use, and CO₂ emissions towards 2050

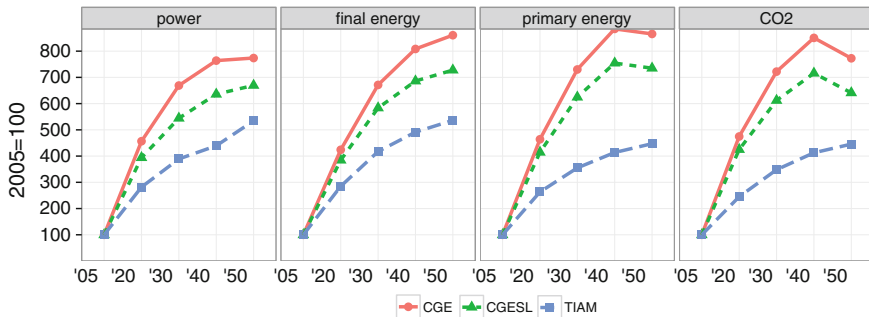


Fig. 7 West-China reference scenario in TD AIM/CGE, BU TIAM and hybrid CGESL models—pathways for power generation, primary and final energy use, and CO₂ emissions towards 2050

The **West-China sub-region** comprises many sparsely populated and economically less developed provinces of China. The corresponding future pathways are provided in Fig. 7. The results are similar to the other sub-regions of China, indicating major differences if models are not soft-linked and used stand-alone under a common reference scenario.

4.4 Discussion

Soft-linking global models with regional China features allows for new, sub-regional insights into China’s future economic and energy system development. The common reference scenario established and tested in this study could provide a basis for future scenario studies about the potential global impacts of China-specific

sub-regional and national energy and climate policies. These results, if replicable, reliable and transparent, could feed into an ongoing energy and climate policy debate in China, which is striving to balance global and China-specific regional development issues.

As previous scenario studies for China showed, the divergence in China-specific scenario results calculated by different modelling tools with different underlying assumptions is rather high (Mischke and Karlsson 2014). Our preliminary results confirm that China-specific modelling exercises should be sufficiently harmonised and documented first, before applying any modelling framework to study policy scenarios for China in a global context.

To cope with the range of uncertainty in China's future energy and emission projections, future work should focus on benchmarking such a global and China-specific modelling exercise with more leading global and China-specific scenario studies. More research is also needed to understand and explore uncertainty in underlying statistical differences that serve as inputs for this and other modelling frameworks.

5 From Global Modelling to Country Analysis: Focus on South America with TIAM-ECN and E3ME

Within the framework of the European research project CLIMACAP³ the global energy system model TIAM-ECN and the global macro-economic model E3ME are linked in order to enhance the energy and economic analysis capabilities focusing on Latin American energy topics.

TIAM-ECN is the TIMES Integrated Assessment Model (TIAM) of the Energy research Centre of the Netherlands (ECN), used for long-term energy systems and climate policy analysis. It has a global scope with a world energy system disaggregated in 20 distinct regions. TIAM-ECN is a linear optimisation model, based on energy system cost minimisation with perfect foresight until 2100. It simulates the development of the global energy economy over time from resource extraction to final energy use.

E3ME is an econometric input-output model of the global economy, energy system and environment. It is maintained and developed by Cambridge Econometrics (CE), and is frequently applied to assess the macroeconomic impact of energy policies and technologies, as well as other energy-environment-economy (E3) interactions. In the CLIMACAP project is applied as a tool to assess the impact of whole energy system scenarios on the wider economy of selected Latin American countries. The model uses a combination of accounting identities and

³ www.climacap.org.

empirically estimated econometric equations to assess the impact of these different energy system pathways on consumers, industries and the economy as a whole. Importantly, E3ME includes a technology defined approach to modelling the power sector, and therefore the scenarios can be made compatible with TIAM-ECN.

5.1 Methods

The two models are aligned in the sense that, firstly, they apply consistent assumptions for global parameters, including fossil fuel prices, carbon prices, technology efficiency and technology costs. Secondly, that the results from the TIAM-ECN model, including capacity and generation figures, energy demand and required investment costs, define model input data that is fed into E3ME. Energy sector results from TIAM-ECN are processed and input to E3ME including:

- Electricity capacity and generation development, by power sector technology;
- Hydrogen capacity and generation development, by hydrogen sector technology;
- Industrial energy consuming technology (production method) CCS capacity;
- Energy demand, by final user and fuel type;
- Energy system investment costs, by technology type;

These inputs are processed before being used in E3ME to convert to the required units of measurement and classifications. As the TIAM-ECN model is solved every 10 year interval to 2050 (focus in CLIMACAP project on horizon until 2050) and E3ME requires annual inputs, the figures for the intermediate years are interpolated from the TIAM-ECN results.

As explained above, a change in electricity prices is modelled in order to account for changes in the cost of power sector investment, transmission costs and CO₂ capture and storage. In all other cases it is also assumed that there is an increase in prices to finance the energy technology investment. There is an increase in prices in the industries that invest in carbon capture and storage (CCS) technology to fund investment in industry CCS. It is assumed that there is an increase in the price of vehicles that is sufficient to cover the investment cost to finance additional investment in vehicles.

Electricity prices, energy system investment, prices of energy-using capital, and fuel demand determine the overall economic impact. There are three channels through which the TIAM-ECN results impact on the economy:

- through the level of investment in energy technologies, and the upstream impact of that investment,
- through the electricity prices and industry costs, and the consequential impact on demand,
- through the mix of energy demand by fuel in the economy and the associated trade balance.

5.2 Results

The results in Fig. 8 show on the left side energy technology expenditures for Latin America and representative selected countries, and on the right side the corresponding macro-economic impact in term of GDP change decomposed by their main effects. The results refer to a scenario with a carbon tax on GHG starting at US\$50 in 2020 and increasing by 4 % per year in real terms. The change of GDP is given versus the baseline development which does not impose any climate policy measures for the future.

For the macro-economic modelling with E3ME a dominating investment effect can be observed for Latin America. The investment is paid for, ultimately, by consumers who see an increase in real household consumption.⁴ In net terms, GDP increases by 1.6 % in 2030, 2.0 % in 2040 and 1.3 % in 2050. The main driver for this dynamic is the shift in the structure of the economy, from fossil fuel supply chains to capital supply chains, which leads to stronger dynamic multiplier effects. A closer look at investments shows for Latin America as whole, and in particular for Brazil and Mexico, that additional investment in the power sector does not crowd out investment in the rest of the economy, since investment in productive assets is not constrained, because it can be withdrawn from investment in non-productive assets. As a result, the impact on GDP in E3ME is a net effect of the increase in investment. In principle, the positive investment impact could outweigh the negative price effects reducing real consumer spending since E3ME allows for spare capacity in the labour market and so demand-side (investment) stimulus can yield positive GDP results. Since many consumer goods are imported, the reduction in consumption leads to a reduction in imports which also impacts on GDP. For Mexico the net impact on GDP mostly reflects two competing factors in the longer term driven by the changing structure of the energy system. As more capital and less fuel intensive technologies come into the energy system a demand for these capital goods (investment) is offset by the extra price of these technologies. The technology outcome matters considerably in the determination of the results, in particular the overall cost and the relative weighting of the capital and operating cost components and the characteristics of those supply chains in the domestic economy. In the early period, the investment effects dominate substantially, but by 2050 the differences are much smaller and the net impact on GDP is only around 1 % at a CO₂ price of \$165/tCO₂ and emissions reductions of over 50 % compared to the baseline. Consumer spending in 2050 is 0.4 % higher than in the baseline due to the recycling of the carbon tax. Colombia's total production could be positive with an increase of up to 2.7 % by 2050, with negative GDP impacts from increasing imports (to meet increasing demand) and reducing exports (as a result of the price effects). The developments of employment under the carbon tax scenario show an increase of employment compared to the baseline by almost 5 million (net additional) jobs (+1.4 %) across Latin America by 2050. New jobs are created in particular in Brazil and in Argentina with a growth of more than 2 % each.

⁴ In the modelling approach applied in this study the carbon tax revenues has been recycled to households.

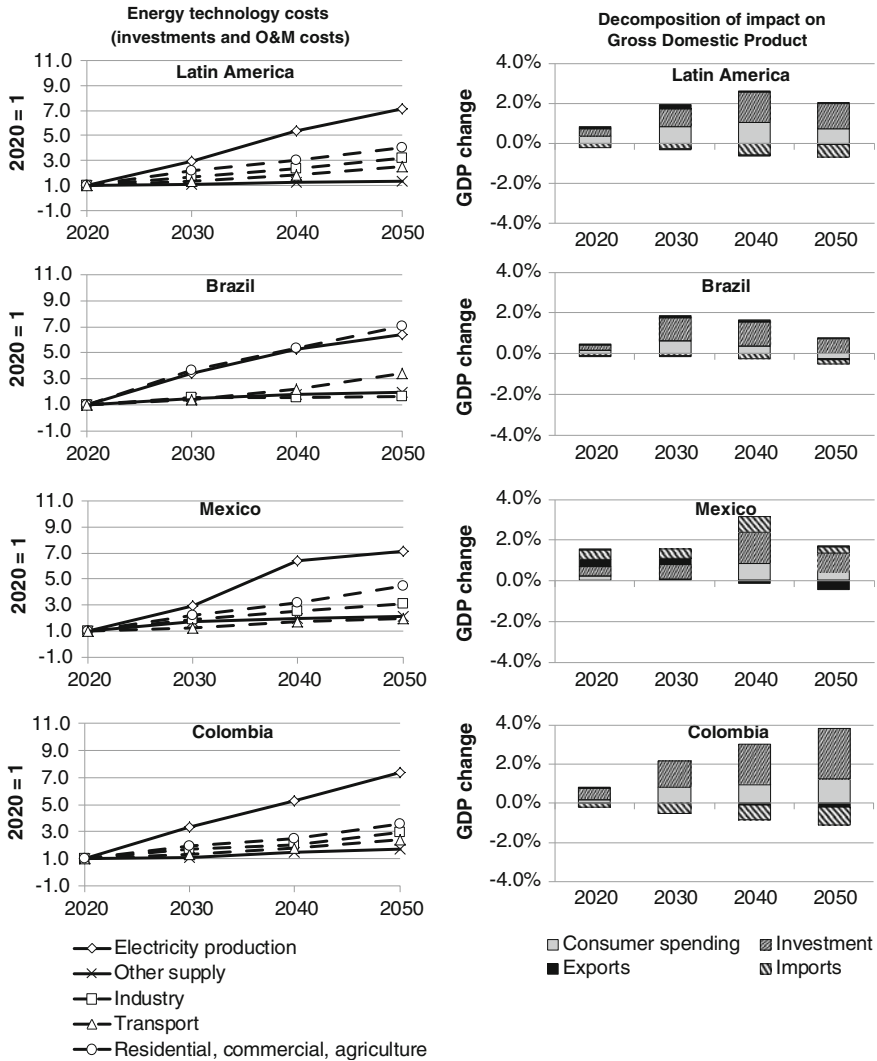


Fig. 8 Energy investments and GDP impact on Latin America under a high carbon tax scenario

5.3 Discussion

Comparing the results from the linkage of TIAM-ECN and E3ME with results from the CGE model, the consequences of increasingly higher carbon prices in terms of reduced consumer spending and GDP are linear in the CGE models and increase as the carbon price increases; but divergent and non-linear in the soft-linked modelling

approach reflecting the explicit definition of physical characteristics of technology in TIAM-ECN and the economic impact of the technologies different economic characteristics as represented in E3ME

The model linkage approach captures detailed technology switching and this is reflected in the non-linearity of the economic results, but the model also yields different results because of fundamental differences in economic structure and approach that allows policy impacts that stimulate the demand side to lead to positive impacts on GDP even in the long term. The outcome of the combined model approach shows that both investments and consumer spending will increase under climate policy, which suggests that the price impacts of more expensive energy due to structural changes to the energy system can be compensated by the impact of the related changes to the structure of the energy system and economy.

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