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Information for a developmental approach to mitigation:

Linking sectoral and economy-wide models for Brazil, Chile, Colombia, Peru and South Africa

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Linking sectoral and economy-wide models for Brazil, Chile, Colombia, Peru and South Africa

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EXECUTIVE SUMMARY

Policy-makers in developing countries are concerned with charting the development path of their economy and society. Providing information on the potential socio-economic benefits of a transition to a low-carbon society requires improved tools to deliver good information for decision-making.

This paper reports on modelling approaches that provide information to answer policy-relevant questions in Brazil, Chile, Colombia, Peru and South Africa. The analysis informs different country contexts: energy-related GHG emissions currently dominate in Chile and South Africa, while those due to agriculture, forestry and land-use (AFOLU) are historically more important in Brazil, Colombia and Peru.

The central methodological challenge addressed in this paper is that of linking detailed models of sectors with economy-wide models. Combining the two approaches holds promise of addressing short- and long-term technological change as well as economy-wide interactions; and direct costs and emissions reductions as well as the broader socio-economic implications. This research report has brought together the main findings from five research teams: the Energy Planning Programme at the Federal University of Rio de Janeiro, Brazil (referred to as COPPE in this report); the Energy Strategic Research Centre, Universidad de los Andes, Bogota, Colombia (UniAndes); Energy Centre, University of Chile, and Pontificia Universidad Católica, Chile (UCh-PUC); the Instituto de Investigación de la Amazonía Peruana, Peru (IIAP); and the Energy Research Centre, University of Cape Town, South Africa (ERC).

The approach taken in this paper is that all teams analyse some form of carbon pricing, be it a carbon tax, emissions trading or gaining credits from market-based mechanisms. Teams also identified additional mitigation actions, relevant to their national context – policy, economy and society.

The approaches to linking sectoral and economy-wide models provided several learnings on methodological issues. Particular challenges were found in integrating AFOLU sectors, with energy sector analysis typically starting with electricity. Disaggregation and alignment of sectors poses challenges. On hard- or soft-linking, various options were explored – hybrid accounts, automated changes and manual exchange. Based on these studies we find that neither hard- nor soft-linking is better, but rather that both have advantages and limitations. On treatment of time, sequential and dynamic approaches seem appropriate (rather than one-shot approaches) to questions of development and climate, since decision-makers need to understand how both economies and emissions evolve over time.

The four research teams that applied carbon prices of $10, $20 and $ 50 used different modelling frameworks, and different policy instruments might be pursued in their countries. All reductions are relative to a reference or business-as-usual case. Reductions in emissions were found to be highest in the UCh-PUC study of Chile, up to 21% at $50 / tonne CO_2-eq, though only applied to the electricity sector. The UniAndes-DNP study showed less than 6% relative reduction in GHG emissions at this tax level; ERC's implementation of a carbon tax in their modelling up to around 3% at most; and COPPE's analysis in IMACLIM-Brazil up to 12%. The report also noted fairly smooth increases in the ERC and COPPE studies, contrasted with inflection points in the UniAndes-DNP and UCh-PUC results. These are not final or definitive findings on possible emission reductions in the countries, but do illustrate the mitigation outcome of carbon pricing.

The socio-economic implications of emission reductions are the key policy question, which this research seeks to address. Based on the work by the modelling teams, it appears that significant reduction can be achieved with a $20 carbon tax, with GDP losses around 0.1% in South Africa as modelled by ERC, 0.5% for in the UniAndes-DNP analysis of Colombia, and 2% in the Chilean power sector as modelled by UCh-PUC, but a 0.6% increase in Brazil's GDP according to COPPE's analysis. The results show that a tax of $ 20 per ton CO_2-eq reduces economic output by less than 2%, comparing GDP in the tax case to BAU, for all the countries studied. It should be noted, however, that the results might also be due to differences in assumed carbon pricing mechanisms, recycling of revenue and the models chosen.

The two studies that examined impacts of carbon pricing on employment and wages found negative effects of a $20 carbon tax, which could be softened only to some extent by recycling of revenue. In the UniAndes analysis of a $20 tax in Colombia, wages decreased very slightly (0.09%), with emission reductions of about 0.5% relative to BAU). The ERC study showed 1% job losses at $ 20, all for unskilled workers. This would be a significant obstacle to implementing the policy; however, it should be noted that full employment is assumed for skilled labour, so further work should replicate these results, and consider shifts of unemployed into employment. The disaggregation of households into declines in the eSAGE model allows analysis of impacts on poor and rich households. The impact of carbon taxes was found to affect rich households slightly more than poor ones. Household consumption, the chosen option for recycling of revenue – via a sales tax – does not have as significant a re-distributional impact on household incomes as expected. Further analysis of moving the unemployed into employment is needed to confirm the robustness of these results – as well as other instruments for recycling.

The analysis by COPPE of a $20 carbon tax in Brazil indicates relative emissions reduce by 10%, with a small increase of relative GDP by 0.6% in 2030. The price index increases by 3.2% in 2030. However, a 8.5% reduction in public debt can be achieved, with appropriate recycling (reducing payroll taxes). Thus emissions reductions are possible with a small increase in GDP, some price increases, a positive in reduction of public debt and reduced unemployment. Overall, the socio-economic implications of these findings for Brazil (Wills 2013; Wills et al. 2014a) are the most positive across the studies reported in this joint paper.

Many mitigation actions were examined by three research teams (Benavides et al. 2014; Delgado et al. 2014b; Merven et al 2014); here the results for those, including renewable energy (RE), are compared. The ERC's analysis found greater emission reductions from its RE scenarios than a carbon tax, but with GDP losses. The decrease of the industrial sector's contribution to GDP outweighs an increase in the electricity sector's contribution, due to lower economic growth – and hence also reducing employment. The UCh-PUC and UniAndes-DNP report similar results: increases in (non-conventional) RE reduces emissions to a similar degree to carbon taxes.

The UCh-PUC found that a further increase of non-conventional RE to 25% by 2030 (25/30) reduces emissions to a similar degree as a $ 10 / t CO_2-eq tax (and 30/30 is comparable to $20 tax). The mitigation action with NCRE has a lower increase in electricity prices (and GDP impact) than carbon taxes with comparable emission reductions. It seems the carbon tax in Chilean electricity sector is not ideal for electricity prices, and investment in more renewables – or indeed emissions limits – might be more optimal. The UniAndes-DNP team similarly found that, in Colombia, a renewable portfolio and industrial electricity programs would achieve a similar mitigation outcome as a $20 carbon tax. GDP losses between these energy programmes were roughly similar to the carbon tax – without recycling at $10, with recycling at $20.

The research teams have identified a number of areas for further work; which are elaborated in the conclusion section 5 below.

Linking sectoral and economy-wide modelling to better understand the socio-economic implications of mitigation pushes the frontiers of knowledge. It has the potential to provide crucial information for decision-making on development and climate. The findings in this report are an important step forward, but in the view of the authors, by no means the final word. Building modelling frameworks that can more fully implement a developmental approach is a long-term and ambitious research agenda. The next step may be to develop frameworks that can model different development pathways, aimed at multiple objectives, and account for the differences in emissions.

1 INTRODUCTION

Policy-makers in developing countries are concerned with charting the development path of their economy and society. In mapping alternative pathways to achieve development objectives, moving to a low-carbon society is perceived as one among several constraints. When mitigation actions or scenarios are proposed, decision-makers want to know the costs. This is particularly true in developing countries, where the opportunity cost of spending on other goods (such as mitigation) in relation to spending on reducing poverty or other development goals is high. Providing information on socio-economic benefits of a transition to a low-carbon society requires more robust and rigorous evidence. Where costs outweigh benefits, it is important to identify the ‘losers’, ways of limiting negative impacts and enabling a just transition also for those sectors and actors.

This paper reports on modelling approaches that deliver information to answer policy-relevant questions in Brazil, Chile, Colombia, Peru and South Africa. The two broad questions relate to what are, firstly, development-oriented approaches to mitigation, and secondly, the socio-economic implications of mitigation actions. Development-oriented approaches will address challenges of reducing poverty, increasing well-being and a range of specific policy question (addressed in each working paper) that relate to national development goals. Research teams working in the MAPS[1] countries have been developing cutting-edge methodologies needed to provide information to answer these questions. Section 2 compares the various approaches that the teams have taken to link technology-rich sectoral models with economy-wide models for analysis.

The analysis in this research report informs five different country contexts. The broader background has been described more fully in a special issue of Climate and Development for each country (Delgado et al. 2014a; La Rovere et al. 2014; Sanhueza et al. 2014; Tyler et al. 2014; Zevallos et al. 2014) and in a comparative analysis, with emerging lessons introduced by the international policy context (Coetzee & Winkler 2014; Garibaldi et al. 2014; Winkler 2014). For this report, the emissions profiles and current debate about carbon pricing is briefly outlined. The joint, comparative analysis contained in this research report builds on working papers by each research team (Benavides et al. 2014; Delgado et al. 2014b; Merven et al. 2014; Vasquez Baos et al. 2014; Wills et al. 2014a).

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[1] The Mitigation Action Plans and Scenarios (MAPS) programme works in Brazil, Chile, Colombia and Peru with local research organisations; the MAPS international team is based in South Africa, a collaboration of SouthSouthNorth and the Energy Research Centre, University of Cape Town. This paper emerged

The five countries differ in their current emissions profile, as illustrated in Figure 1. Energy-related GHG emissions currently dominate in Chile and South Africa, while those due to agriculture, forestry and land-use (AFOLU) are historically more important in the other three countries.

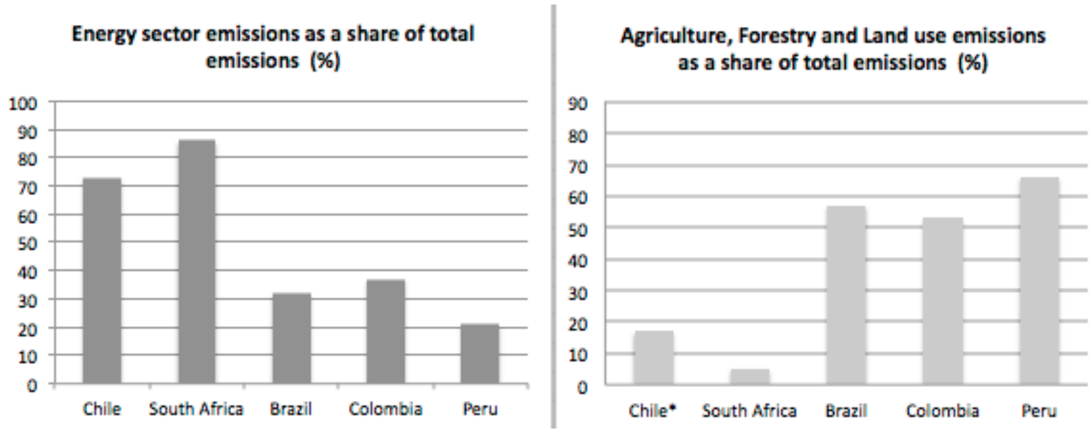

Figure 1: Emission profiles of the countries studied, for energy and AFOLU sectors

Note:

Reference year for Peru and South Africa is 2000. That of Colombia is 2004, Chile 2006 and Brazil 2010.

***Only emissions from the agriculture sector are included for Chile. The AFOLU balance for Chile is net negative, that is, a sink.**

Undertaking research in these country contexts, and given the broad questions that inform decision-making, the research teams[2] identified more specific policy questions. The approach taken in this report is that all teams analyse some form of carbon pricing, be it a carbon tax, emissions trading or gaining credits from market-based mechanisms. Teams also identified additional mitigation actions that are policy-relevant. In this way, some comparison is possible across carbon pricing, while the diversity of mitigation actions is also analysed. These mitigation measures, country-specific mitigation actions, and its analysis are presented in section 3.

The policy context and choice of instrument may differ for carbon pricing. Brazil, Chile, Colombia, and South Africa considered a carbon tax: Brazil uses carbon taxes as a proxy for emissions trading, noting that actual policy may differ – and no direct carbon pricing in either form might be applied in some cases, for example, to transport because of the difficulties in monitoring emission; the new Chilean government is considering a $5 / tonne of CO_2 tax on fossil fuel generation, thus mainly affecting the electricity sector, to start from 2017; in Colombia, an indirect carbon tax – in the form of a cost of fossil fuels – is a possible policy instrument, with the Ministry of Finance drafting a 'green tax' law in 2012; and, in South Africa, National Treasury which favours a carbon tax, issued a policy paper and indicated that the first period of implementation would be from 2016-2020. Emissions trading schemes seem to be considered more favourably than a carbon tax in Brazil, explored as instrument in the Chilean energy sector, while the South African Treasury has issued a paper on project-based off-sets. Finally, it seems inappropriate to have carbon pricing in the Peruvian forestry sector, so the analysis by the Instituto de Investigación de la Amazonía Peruana (IIAP) focuses on incentives (derived from oil royalties) that could be provided by public institutions for agroforestry in secondary forests, and possible links to carbon credits. In all cases, the use of revenue from tax income, sale of allowances or credits is crucial to the distributional and socio-economic implications. These implications are further explained in section 4.

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[2] The research teams are the Energy Planning Programme at the Federal University of Rio de Janeiro, Brazil (referred to as COPPE in this report); the Energy Strategic Research Centre, Universidad de los Andes, Bogota, Colombia (UniAndes); Energy Centre, University of Chile, and Pontificia Universidad Católica, Chile (UCh-PUC); the Instituto de Investigación de la Amazonía Peruana, Peru (IIAP), the Energy Research Centre, University of Cape Town, South Africa (ERC).

Each research team also uses their linked modelling method (see section 2) to analyse country-specific mitigation actions. Renewable energy (RE) is considered by quotas in Chile, and through an independent power producer (IPP) procurement programme in South Africa. Low carbon-scenarios are examined in Brazil, which consider mitigation measures in different sectors like energy sector, industry, transport and LULUCF. The UniAndes team in Colombia examined the implementation of carbon taxes, equivalent carbon caps, a renewable generation portfolio, and a fossil fuels substitution in the industrial sector programme.

The conclusions derived from the country studies are summarised in section 5. These conclusions include the key methodological learnings related to linking sectoral specific and economy-wide model. Results obtained from this modelling exercise, both on mitigation and its socio-economic implications, provide some initially insights – as well as proposals for further work and improvements.

2 METHODOLOGIES

The central methodological challenge addressed in this report is that of linking detailed models of sectors with economy-wide models. The methodological challenge is of interest in its own right, but its key purpose is to provide decision-makers with information on the emissions associated with different development paths, and the socio-economic implications of mitigation. This section considers the different modelling tools and approaches to integration that the research teams have adopted to tackle the methodological challenge.

2.1 Combining sectoral and economy-wide models

The key methodological challenge addressed in this work has been the linking of sectoral and economy-wide models. Historically, models used for mitigation analysis have been ‘bottom-up’ engineering models providing technology-rich information on particular sectors (e.g. electricity, broader energy, land use, forestry, transport) and ‘top-down’ economy-wide models, which are based on information of financial flows throughout the economy and include indirect effects. Economy-wide models tend to be applied with shorter time-horizons and reflect rigidities in economies through fixed technical coefficients. Sectoral models are typically better at representing technological change, and are applied over longer time-horizons (20, 30 or even 50 years, albeit with increasing uncertainties). The Intergovernmental Panel on Climate Change (IPCC) noted already in its 2nd Assessment Report (IPCC 1996) that bottom-up models tend to find low and even negative mitigation costs for many mitigation actions; while economy-wide models tend to show high costs in terms of GDP losses for low-carbon development pathways or exhibits lower reductions in emissions compared with sectoral models. Combining the two approaches holds promise of addressing short- and long-term technological change as well as economy-wide interactions; direct costs and emissions reductions, as well as the broader socio-economic implications. Significant effort is needed to link different models, and to ensure there is accurate ‘translation’ between researchers from different disciplines.

2.2 Comparison of model choices

Many different models are available and research teams build on analytical frameworks they have built up over time. Table 1 shows a comparison of the different methodologies used in overview. More detailed descriptions of the model used by each research team are contained in their working papers (Benavides et al. 2014; Delgado et al. 2014b; Merven et al. 2014; Vasquez Baos et al. 2014; Wills et al. 2014a).

Considering economy-wide models, most of the research teams use some form of computable general equilibrium (CGE) model; while the Chilean team adapted a dynamic-stochastic general equilibrium (DSGE) model. The DSGE model was initially developed in the Central Bank of Chile, and adapted with the assistance of the Ministry of Finance to introduce energy price shocks to Chilean economy. Among CGE models, some frameworks were also developed for global analysis: for example, IMACLIM was developed as a global model, then applied for national analysis in France and applied by the COPPE team to Brazil.

The ERC team worked with a CGE model for South Africa developed for National Treasury by UNU-WIDER, based on the standard IFPRI model. The South African CGE model was extended to include a more detailed energy sector. Another key distinction is whether comparative static analysis (comparing two states of the economy, no explicit representation of time) or dynamic-recursive CGE models are used, – for example the MEG4C model developed by the Department of National Planning in Colombia and used, in this study (Delgado et al. 2014b), by the UniAndes-DNP team.

Sectoral models are diverse, and focused on models for energy planning (Markal, TIMES, LEAP, others); including both energy use and supply; and analytical tools for AFOLU, where analysis is more spatially specific. The methodology therefore focuses on the two largest general categories of emissions and, so, mitigation potential (AFOLU being larger than global average in Latin America).

Given that emissions in AFOLU sectors dominate in Peru, contributing more than 50% of total GHG emissions, the focus of mitigation may not lie in pricing carbon, but in means to increase carbon sequestration in the biomass of trees. The IIAP team investigated agroforestry systems as a sequestration option, starting with a biometric model that focused on suitable tree species (selected by evaluating growth rate, timber value, and farmer perception). The team adjusted an econometric model using the generated data (from Chave et al. 2005) for specific trees, and compared the benefits and cost of investment for the establishment of agroforestry systems and compared the benefits with the price of certified emission reductions (CERs, carbon credits under the Clean Development Mechanisms for afforestation).

The remaining teams focused on the energy sector and used several models to study it. These can be broadly distinguished as simulation or optimising models; both were used by the teams, as can be seen in Table 1. The Chilean research team used a simulation tool in order to assess the national power sector. On the other hand, optimisation models such as MESSAGE, MARKAL and TIMES –all least-cost partial equilibrium models– were used by the Brazilian, Colombian and South African research teams to model their respective national energy systems. Some of the research teams calculated energy demand in LEAP or spreadsheets, and use this as an input to models optimising energy supply to meet exogenous demand. Others (Brazil and South Africa) used the economy-wide model to project demand.

In addition to these sectoral and economy-wide models used, Table 1 also reports on the level of disaggregation in the economy-wide models and integration of models. For integration, the broad approach taken by each research team is described in Table 1, and elaborated in greater detail in section 2.3.

Table 1: Comparison of methodologies for linking sectoral and economy-wide models by five research teams

	COPPE, Brazil	UniAndes, Colombia	UChile-PUC, Chile	IIAP, Peru	ERC, South Africa
Methodology					
Economy-wide model	IMACLIM- Brasil (static CGE model)	MEG4C (recursive dynamic CGE model) M (endogenous growth model)	DSGE (adapted from the model developed by Medina & Soto, (2007))	No economy-wide model, econometric model used as part of analysis	e-SAGE (recursive dynamic CGE used sequentially) and with re-calibration capability. Exogenous integration of electricity expansion plan
Sectoral models	MESSAGE for power sector and refineries Work in progress Electrical and refining sectors Energy demand AFOLU (BLUM)	MARKAL (electricity sector), MARKAL also used as accounting reference for other sectors	Centralized electricity planning model provides electricity prices	Biometric model for specific timber trees and aboveground biomass and carbon. Added agroforestry systems to existing analysis	TIMES (energy model)
Sectoral disaggregation	19 economic sector 50 sectors version under development	MEG4C: 16 economic sector M: 1 economic sector MARKAL: 6 users of energy	3 sectors, one produces intermediate inputs, another that ensembles the consumption good and the third one is copper	n/a	61 sectors in the CGE. Only power sector in energy model
Model integration	IMACLIM, with MESSAGE for power sector and refineries. Work in progress Electrical and refining sectors Energy demand AFOLU (BLUM)	M provides GDP projections to MEG4C; MEG4C provides sectoral GDP to MARKAL; MARKAL provides M with total energy costs	Electricity planning model provides electricity price to the DSGE economy-wide (steady-state economy, full employment – not growth model)	Starts from biometric model, to adjust Peruvian data in econometric model, for the agroforestry sector Compares cost-benefit of investment to CER prices	Exogenous integration of electricity expansion plan from TIMES with e-SAGE (CGE with energy extension based on standard IFPRI model)

2.3 Approaches to integrating modelling systems – linking sectoral and economy-wide models

Various analytical challenges arise when linking sectoral and economy-wide models. Some of these challenges are illustrated in Figure 2 and presented in the next subsections: issues of communication between the two models; treatment of time; trade-offs between model accuracy and requirements of stakeholder processes; and level of integration of sectors within the economy-wide model. Each of these challenges is described below.

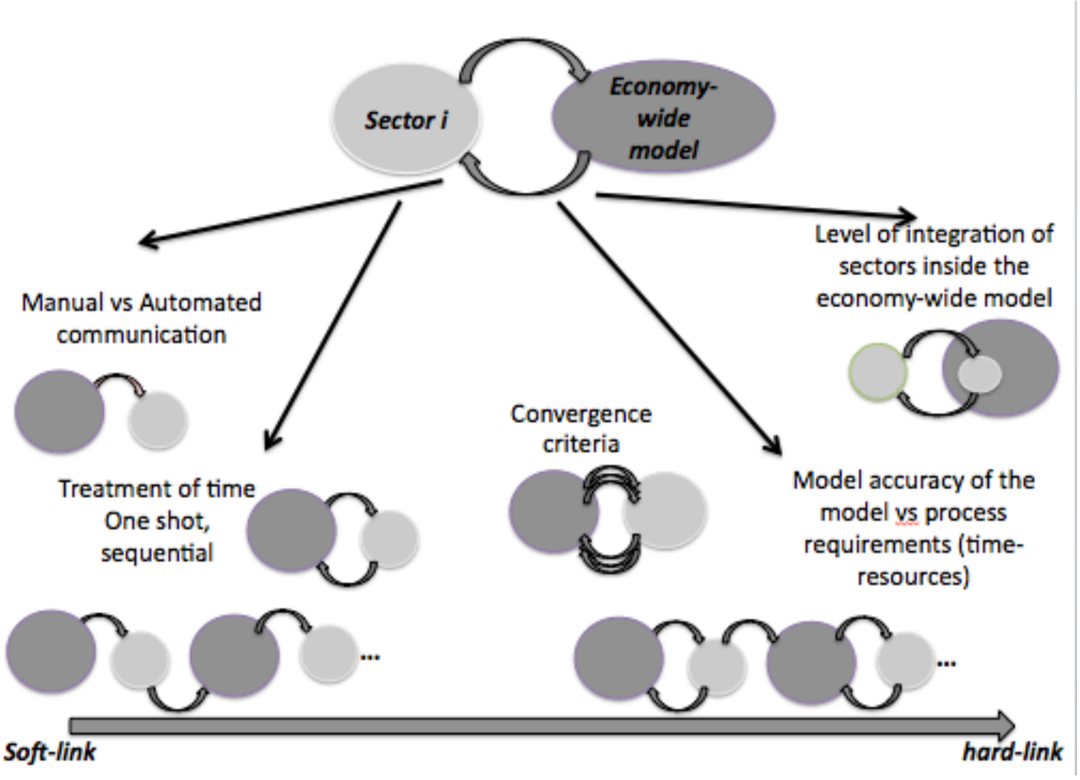

Figure 2: Various challenges in linking sectoral and economy-wide models

2.3.1 Communication between the two models

Central to linking models are the issues of which models communicate with each other, what information is passed from one to the other, and whether this process is manual or automated. In several cases, energy models pass information on energy investment plans and prices to the economy-wide model.

The COPPE team would take information on energy prices, matrix and total investments from LEAP and MESSAGE into the IMACLIM model, essentially a CGE model adapted to represent the Brazilian economy. IMACLIM in turn provides MESSAGE with information on energy demand and energy prices, which MESSAGE uses to determine the energy matrix and the total investment needed. Information is passed back and forth until energy prices and demand converge. For the present analysis, key results, however, are from the IMACLIM model (Wills 2013), with bottom-up considerations reflected in hybrid accounts, MAC curves for Brazilian industry and link with MESSAGE for power sector only. Fuller linking is part of continued work (see section 5 below).

Similarly for South Africa, given an initial demand, TIMES computes an investment plan and a resulting electricity price projection, which is passed to the eSAGE model for South Africa. The production schedule and capital growth are also gradually imposed. ESAGE then uses the information to calculate sectoral energy demand and fuel prices, going back into TIMES in the next iteration. Again, energy prices and demand are expected to converge (typically in about three iterations).

The Chilean researchers use models for the industrial, transport and commercial, public and residential (CPR) sectors for a bottom-up projection of electricity demand. In the first iteration, the sectoral models are run using an exogenous projection of GDP values. Demand projections simulated in the sectoral models are then used as input to the electricity expansion-planning model. The electricity expansion-planning model then calculates an electricity price using the carbon tax and the exogenous demand as inputs (note that demand is given and the expansion plan calculates the price for each level of tax). The estimated price is passed as an input to the DSGE model, which provides the response of GDP to electricity price variation due to the carbon tax.

The Colombian team linked three models in the following sequence. First, an endogenous growth model (M) provides the CGE model (MEG4C) with overall GDP projections. Secondly, MEG4C produces sectoral GDP, and passes these as energy demand drivers to the energy model (MARKAL). Third, MARKAL optimises the energy sector and provides M with new annual total energy costs. The idea behind the three-model approach is that GDP growth is inversely related to the cost of energy: higher energy costs mean less money available for either consumption or investment; this translates into less investment on productive capital and lower GDP growth. In turn, lower GDP growth leads to lower energy demand, and lower energy costs, which raise GDP. The process iterates until convergence in annual energy costs is achieved. Since information is passed manually between the models, the researchers allow a certain tolerance.

The ERC has created a module, written in GAMS programming software, that passes information between eSAGE and SATIM, so automated to that extent. The Colombian, Brazilian and Chilean cases illustrate approaches of manual communication between models, sometimes referred to as ‘soft-linking’ models.

The specific characteristics of AFOLU are reflected in a different approach taken for the Peruvian study. The IIAP team used an econometric, rather than economy-wide general equilibrium model. Rather than sectoral models, a biometric model integrated agroforestry, as a mitigation option with tree timber species suitable for sequestration. These results could be compared with those from an econometric model. The benefits and costs of investing in agroforestry were compared to the price of small-scale CDM projects in afforestation. The link to carbon pricing is thus much more indirect, and considered by the team as more appropriate in this sector.

The experiences do not suggest that either hard- or soft-linking is better, but rather that both have advantages and limitations. The desire to have convergence lends itself to automation, saving researchers time in passing information from one model to another. It also is less prone to human errors than manual copying. However, automated links have to be established. In the process of establishing automated links, the researchers have carefully validated results. The quality of results of automated links is only as good as the intuition shown in this process. With manual communication, researchers are examining results along the way. Convergence can be assessed within a certain tolerance, requiring active engagement of the researchers. Another advantage of this approach remains that it is more transparent to non-experts (less of a ‘black box’).

2.3.2 Time management

The timing of the interactions within the planning horizon between the sectoral and economy-wide models requires careful treatment. While differing in detail, the COPPE and UCh-PUC teams ran models in a one-shot approach, while UniAndes and ERC modellers ran their models iteratively until they converged.

The COPPE team used a static version of the IMACLIM model and hence adopted a one-shot approach. In the case of Chile, a set of scenarios for the power sector model is built, based on variables such as technology prices, fuel prices or restrictions to the use of the national hydro potential. As result, there is a set of electricity prices that are used to feed the DSGE model; as in the case of the Brazilian team this is a one-shot approach. The DSGE takes the electricity price shock (due to carbon tax, for example) and delivers the impulse-response function of GDP. Thus, it is possible to see the trajectory of the GDP during the transition to the new steady state. Upon reaching the new steady state the economy will grow at similar rates before imposing the tax because of the improvements in productivity and population growth, but this growth will be based on a lower level due to lower growth rates in the transition period.

The Colombian and South African teams used a sequential approach. In the case of Colombia the set of models are run one after the other, each optimising throughout the entire time horizon. The procedure is repeated until the change in the sectoral GDP is less than a certain tolerance for all the periods. On the other hand, in the South African model, the economy-wide model, operating in recursive dynamic mode with no foresight (myopic) is used to make electricity demand projections. These projections are then passed onto the power sector model, which has perfect foresight and is able to prescribe investments required in the power sector, taking account the long lead times of some of the technologies. The impacts on capital requirements and electricity prices of these investments are then passed back to the economy-wide model, which can then readjust the demand projections accordingly in the next iteration. The two models are iterated several times, and convergence is normally reached within three or four iterations.

2.3.3 Level of integration of sectors within the economy-wide model

The degree to which sectoral information is represented in economy-wide models is another important challenge.

In the case of IMACLIM-Brazil, a hybrid set of accounts of physical flows, validated to the National Energy Balance (NEB) (EPE 2013) is reconciled with the Social Accounting Matrix, which takes monetary flows from the national accounts (IBGE 2010). A double accounting system keeps these two matrixes (SAM and NEB) permanently connected via a third one, the price matrix, which is variable and endogenous to the model. For further details, see the research paper on IMACLIM-Brazil (Wills et al. 2013).

The integration of the energy sector in the South African model is similar to that of Brazil, with the energy balance used to calibrate the economy-wide model. The interaction between SATIM and eSAGE is only in the power sector.

One of the problems Colombian modellers found was in respect of the disaggregation of the CGE. In fact, MARKAL considered a whole set of generation technologies, but DANE's 2 digit SAM –the foundation of the MEG4C – was too aggregated. For instance, MARKAL considers electric generation with coal, hydro, natural gas and oil derivatives; while MEG4C considered all this as a single electricity sector with a fixed production function. This was a major shortcoming and led the researchers to implement a different linking strategy. Part of the future work of the Colombian team involves disaggregating the energy sector in the MEG4C and the industrial sector in MARKAL Colombia.

2.4 Summary on methodological aspects of linking strategies

The challenge of linking arises out of the need for a better representation of change, to provide more robust evidence to decision-makers. This requires *both* detailed understanding of sectors and the full implications across economy and society.

Table 2 summarises the diverse responses by the five research teams to the complex methodological challenges of linking detailed models of sectors with economy-wide models. The main conclusions on these methodological aspects are picked up in the overall conclusion (section 5 below).

Table 2: Comparison of linking strategies across five studies

	COPPE, Brazil	**UniAndes, Colombia**	**UChile-PUC, Chile**	**IIAP, Peru**	**ERC, South Africa**
Linking strategy					
Information exchange	Iterative IMACLIM - MESSAGE → Demand, fuel prices ← Energy matrix, electricity prices	M→ (GDP) → MEG4C →(Sectoral GDP) → MARKAL→(total energy costs) → M	DSGE – Electricity planning sector → GDP ← Electricity prices from energy model (centralized planning) iteratively	IIAP-Peru did not use sectoral models, but econometric model, in three stages: 1) Use biometric model, calibrated to Peru to provide aboveground biomass and carbon; 2) introduce agroforestry systems in analysis; 3) compare cost-benefit of Agroforestry systems to actual price of CERs	CGE passes information on demand and input fuel prices to TIMES. TIMES passes back electricity generation mix, electricity price and investment
Convergence criteria	Energy price and demand should converge in MESSAGE and IMACLIM after some iterations	Mean absolute deviation between GDP growth in M and MEG4C lower than 5*E-4	Electricity price and GDP should converge in both Electricity and the DSGE 1 model after some iterations		Energy price and demand should converge in eSAGE and TIMES after some iterations
Communication of the models	Soft link	Soft link	Soft link	n/a	Hard link

Treatment of time	One shot	Sequential	Dynamic	n/a	Sequential
Number of sectors integrated in economy-wide model	19 sectors	MEG4C: 16 economic sector M: 1 economic sector	3 sectors	No detailed sectoral models developed, so no integration	

3 MITIGATION ANALYSIS OF CARBON PRICING

This section examines the mitigation outcomes of carbon pricing modelled by the research teams. Placing the analysis of mitigation outcomes first is not a matter of priority over socio-economic development; indeed the added value of linked models relates to socio-economic benefits of a transition to a low-carbon economy and society – which are reported in section 4. To build the case towards this key information, the results for mitigation are reported in this section 3. Section 4 adds analysis of mitigation actions but, as these are different in each country, the discussion starts with carbon pricing, which – at least in respect of assumed tax levels – is comparable across these studies.

The results of analysis of carbon pricing are summarised in Table 3. The research teams included three tax levels ($10, $20 and $50 / ton CO_2-eq), in addition to others that may have particular relevance in national discussions, to enable a comparison. Yet it must be understood that different assumptions were made about the particular mechanism for carbon pricing (carbon tax, emissions trading, CERs, etc.) represented in the modelling, the recycling of revenue, as well as the different models used (as outlined in section 2).

Table 3: Emission reductions relative to BAU in 2020 or 2030 resulting for carbon prices across five studies

	COPPE, Brazil	UniAndes, Colombia	UCh-PUC, Chile	ERC, South Africa
$ 10 / ton CO_2-eq	86.3 Mt CO_2 eq. from energy sector: 9.3% reduction relative to BAU (in 2030)	0.39 Mt CO_2-eq; 0.18% reduction relative to BAU (in 2020)	[0.3 to 2.6] MtCO_2-eq; [0.7 to 6.4]% reduction relative to the corresponding base scenario (in 2020)	5.25 Mt CO_2-eq; 1.01% reduction relative to BAU (in 2020)
$ 20 / ton CO_2-eq	94.5 Mt CO_2 eq. from energy sector: 10.2% reduction relative to BAU (in 2030)	0.90 Mt CO_2-eq reduced; 0.41% reduction relative to BAU (in 2020)	[0.5 to 3.5] MtCO_2-eq; [1.2 to 9]% reduction relative to the corresponding base scenario (in 2020)	10.35Mt CO_2-eq; 2.00% reduction relative to BAU (in 2020)
$ 50 / ton CO_2-eq	112.2Mt CO_2 eq. from energy sector: 12.1% reduction relative to BAU (in 2030)	12. 6 Mt CO_2-eq reduced; 5.77% reduction relative to BAU (in 2020)	[6.2 to 8.4] MtCO_2-eq; [15.7 to 21.1]% reduction relative to the corresponding base scenario (in 2020)	14.25Mt CO_2-eq; 2.75% reduction relative to BAU (in 2020)

Recycling of revenue	Yes, Recycling can be modelled as reductions in public debt, reductions in payroll taxes, or lump sum to households (green cheques) Results presented here assume the recycling scheme is by reductions in payroll taxes	The results presented above do not include the recycling mechanism With recycling through direct transfers to the households there is abatement of 0.38, 0.91 and 12.55 Mt CO_2-eq for carbon taxes of \$10, \$20 and \$50 respectively	No recycling is considered	Yes, recycling through reductions in sales/VAT taxes
Comments	Above results are for 2030. The static version of IMACLIM was used	The BAU scenario accounts emissions for all the sectors except LULUCF and Waste sectors. The tax was only imposed on the energy sector	The carbon tax is applied between 2017 and 2030 to both SING and SIC power systems. Only the electricity sector is taxed	Above results are with conservative learning rates for RE technologies Escalating carbon taxes, start at lower levels with \$10 and \$20 reached in 2025 and \$50 in 2030 for respective scenarios

The results in Table 3 above show that there are significant differences in emission reductions relative to BAU reported for the same tax levels. It is important to emphasise that this may reflect differences in the modelling approaches, or particular instruments assumed, or differences in the responsiveness of the economies to a carbon price. It may be a function of elasticities of substitution among sources of energy, or due to different responses of the real economies. To the extent possible in the bottom-up methodology adopted in this report, the reasons for differences are explained.

3.1 Overall results

The percentage change in relative emission reductions is highest in the UCh-PUC study of Chile (Benavides et al. 2014), between 0.3% and 21.1% for \$10 and \$50 per ton CO_2-eq. By contrast, the study for Colombia changes of less than 6.0% in emissions relative to BAU for the same tax levels (Delgado et al. 2014b). In between lie the results of the case study for South Africa, which reports between 1.0% and 2.8% for a carbon tax (Merven et al. 2014);[3] and the COPPE study of Brazil, between 9.3% and 12.1% (Wills et al. 2014a).

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[3] It should be noted that other economic sectors have not yet been fully integrated in the current linked-model hence emissions reductions for South Africa could be over-estimated.

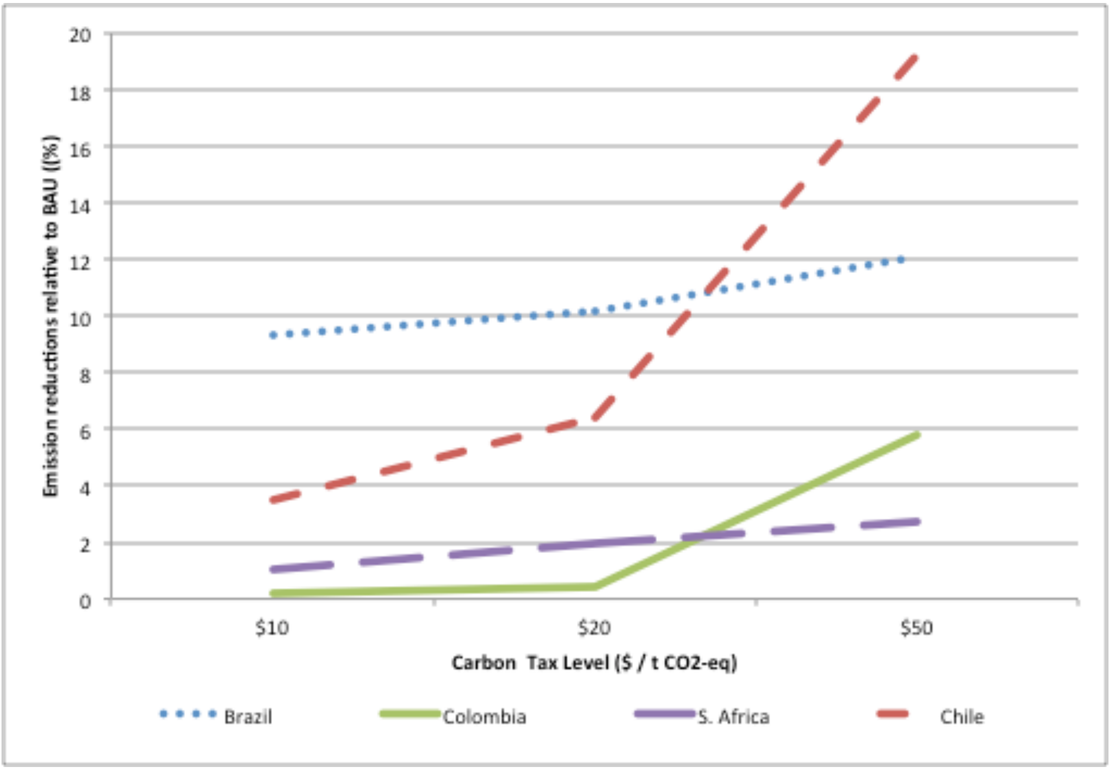

Figure 3: Emission reduction relative to BAU (%) for different carbon tax levels ($ / t CO_2eq)

There are clear inflection points in the UniAndes-DNP and UCh-PUC studies of carbon pricing. In the Colombian case, this inflection shows the point where a new technology becomes part of the optimal energy scenario. The ERC and COPPE studies show fairly smooth increases for rising levels of carbon price, which suggests this may be function of smooth modelling assumptions. In the ERC analysis for South Africa, emission reductions relative to BAU rise up to $20, but then there are diminishing returns to higher tax rates in South Africa. The reverse is true in the Chilean electricity sector, where modelling of a $20 carbon tax still shows relative reductions in the range of 1.2 and 9%, but a higher level of almost 21% of emissions is achieved at $50. The main explanation for this phenomenon is the important generation of coal based power plants, firstly substituted by non-conventional renewable energy (NCRE) with the carbon tax price signal.

3.2 Country-specific aspects of carbon pricing

For a more nuanced understanding of these results, the specific analysis undertaken by each team needs to be understood.

The Chilean researchers also investigated the impact of other mitigation actions (Benavides et al. 2014). It is important to note that carbon pricing in the Chilean study applies to the electricity sector only, since electricity is responsible for most of the CO_2 emissions (40%). Scenario 1 is considered as reference for the comparison. The analysis of a law on NCRE quota as a mitigation action (see Table 5 below) shows that the increase of electricity prices for NCRE is lower than for a carbon tax with similar emission reductions. This may be due to the additional variable costs of coal power plants imposed by the tax.

The UCh-PUC team also analysed carbon caps in the Chilean electricity generation sector, equivalent to tax levels of $10, $20, $30 and $40; emission caps were calibrated to resulting emissions for that tax level. While the mitigation outcome is the same (by design), the results show a lower increase in electricity prices compared to the carbon tax cases; therefore, the impact on GDP will be lower. The Chilean case study thus suggests that the carbon tax may have higher impacts on electricity prices than a CO_2 tax with emission caps reaching the same emissions reductions (Benavides et al. 2014).

The UniAndes-DNP study also evaluated a cap on emissions of $CO_{2,}$ equivalent for each tax level, (Delgado et al. 2014b). By design, levels of abatements were the same, but emissions were found to follow different pathways over time. Generally, abatement due to the cap occurred later than with carbon pricing. The UniAndes analysis thus suggests that carbon pricing yields earlier emission reductions than an equivalent cap. In 2020, the cap equivalent of a $10 tax emissions of 0.01% relative to BAU in 2020; decreasing slightly (0.05%) for the cap calibrated to $20 effects; 4% at a cap set to the result of $50 carbon tax.

Analysis of a carbon tax in Brazil showed a sharp reduction of emissions relative to BAU up to $20 (or R$45/tCO_2). The COPPE team reported that, beyond these tax levels, no further mitigation options were available, so the economy-wide model could not respond with emissions reduced to actions. At higher tax levels, further emission reductions are rather due to the recessive impact of the carbon tax. The recessive impact is heightened when the option of recycling carbon revenue to pay government debt is chosen – further lowering emissions due to this effect (Wills et al. 2014a). This because the other recycling options, such as the reduction of payroll taxes and lump-sum transfers to households, increase consumption and may boost production in economy, as found in Wills (2013).

For all the carbon tax scenarios considered by the ERC, there is little opportunity to reduce emissions in South Africa before 2020, as investments in coal-fired power stations are locked-in, with construction under way. This is the main explanatory factor for emissions reductions of less than 3% relative to BAU achieved in 2020, even with a high carbon tax rate of $50. However, although the impact of a $10 carbon tax on reducing emissions is still small in 2040 (2.75%), carbon taxes of $20 and $50 could result in much higher emissions reductions of 24.26% and 34.05% respectively, relative to BAU, as there are no constraints on investment in the long term (taken here as 2040).

In addition to the tax levels considered by all teams, the ERC team analysed a $5 / t CO_2-eq tax in South Africa, approximating in the analysis Treasury's proposal for a carbon tax, which has a nominal value of R120, a basic tax free threshold of 60% – hence effectively R48 ($5) (National Treasury 2013). The tax is proposed increase annually, reflected in the model as increasing from the initial value of $5 in 2016 to $12 in 2025, which resulted in emissions reductions of 1.76% (9.09Mt CO_2-eq) in 2020. This seems to imply that the current design of the carbon tax will not contribute much to the achievement of South Africa's target of reducing emissions by 34% by 2020 and 42% by 2025 relative to BAU.

An escalating tax rate starting at $3 in 2016, increasing to $ 50 by 2030 was explored for this comparison. Results showed intermediate relative reductions of 2.75% relative to BAU in 2020 (14.25 Mt CO_2-eq) indicating that a bigger carbon tax would still have a very small in the short-term. When the analysis of the carbon tax was extended to 2040, results showed that emissions reductions of 3.16% and 34.05% relative to the BAU could be achieved. This implies that even in the long term the $5 carbon tax would still have a small impact but the higher tax rate would lead to significant emissions reduction.

3.3 Agroforestry incentives in Peru and CER prices

The study by the IIAP team of interventions in Peruvian forestry is different; reflecting both differences in the country's sector and modelling approaches (Vasquez Baos et al. 2014). The combination of biometric and econometric analyses provided a means of exploring innovative approaches to incentives for agroforestry, on the understanding that carbon pricing is probably not the most appropriate in a sector on which people's livelihoods depend very directly. The study focuses rather on benefits that farmers may receive through the implementation of agroforestry systems, and whether revenues obtained are large enough to warrant farmers' investment. The link to carbon pricing is made via CERs, asking whether CER prices in small-scale projects are sufficient to incentivise famers to implement and maintain agroforestry systems. Key considerations that emerge include those not related to price; the preservation of trees for an optimal 30 years is not supported by current CER prices, though earlier carbon prices (Euro 12 / CER) would have been. Given the thirty-year time horizon, emission reductions up to 1.15 Mt CO_2-eq may be possible. This might also make it attractive for regional and local government to invest in these conservation projects, investing public funds to promote agroforestry (Vasquez Baos et al. 2014).

4 IMPLICATIONS FOR SOCIO-ECONOMIC DEVELOPMENT

The implications of mitigation for socio-economic development are a key concern of these studies. Having elaborated the methodologies (section 2) and mitigation results (section 3), the report now turns to results for economic output, employment, inequality and other socio-economic factors.

Table 4: Key implications of carbon pricing at $ 20 / ton for socio-economic development across four case studies

	COPPE, Brazil	UniAndes, Colombia	UCh-PUC, Chile	ERC, South Africa
Socio economic impact				
Macro-economic indicators	0.6% increase in GDP in 2030 compared to reference scenario Price index increases by 3.2%in 2030 compared to reference scenario. 8.5% reduction in public debt in 2030 compared to reference scenario	GDP decreased by 0.56% relative to BAU in 2020, carbon tax (and equivalent carbon cap)	Decrease in equivalent average annual GDP growth rate (BAU is 3,5%) Scenario 1- % [3.11-3.43] Scenario 2- % [3.18-3.42] Scenario 3- % [3.16-3.44] Scenario 4- % [3.11-3.43]	GDP decreased by 0.13% relative to BAU in 2020
Employment	Unemployment is at 5.83% in 2030 compared to 6.86% in reference scenario	Model did not allow for the analysis of changes in employment. Instead wages were assessed. In 2020, for a $20 carbon tax (and equivalent carbon cap), wages decreased by 0.09% relative to BAU	Current version of the model did not allow for employment analysis	There will be 1.06% less new jobs created relative to BAU by 2020. All these will be for unskilled labour

Inequality in income	No impacts on income distribution from this version of the model (Wills 2013)	Model did not allow for inequality analysis	Model did not allow for inequality analysis	Per capita consumption of poor households would decrease by 0.21% relative to BAU in 2020 whilst rich households would have a decrease by 0.24%
Recycling and relation to results	Above results are with recycling through reduction in payroll taxes	In 2020, for a $20 carbon tax with transfer to households, GDP decreased by 0.54% with respect to BAU and wages decreased by 0.15% with respect to BAU	No recycling	Above results are with recycling through reduction in sales tax/VAT

Key results are summarised in Table 4 above, for a tax rate of $20, across the studies by COPPE, UCh-PUC, UniAndes-DNP and ERC. The model of analysis used by IIAP in for the agroforestry sector does not include macroeconomic variables in the same way.

4.1 Socio-economic implications of carbon pricing

This section discusses these socio-economic implications of pricing carbon in turn, as well as the potential for use of revenue from carbon pricing to ameliorate any negative socio-economic implications: impacts on the economy as a whole (to the extent that is captured by GDP), but also socio-economic implications beyond growth, such as effects on (un)employment, wages and inequality. Four research teams examined carbon prices of $10, $20 and $50, using their various modelling approaches.

For a $20 carbon price, and the associated emission reductions (see section 3.1), GDP losses relative to BAU range from around 0.13% of GDP (ERC study) to 0.5% (UniAndes), and 3.3% (range for scenario 1: 3.11–3.43%) by the UCh-PUC, Chile, but an increase of GDP by 0.6% in the COPPE study of Brazil. The latter, however, is an analysis of carbon pricing in the power sector, without flexibility across the entire economy. Three studies do attempt to consider the dampening effect on GDP losses through revenue recycling – in Brazil through payroll taxes (Wills et al. 2014a); by reduced sales tax in South Africa (Merven et al. 2014); and, to the extent as just explained, for Chile in reduced GDP (Benavides et al. 2014).

The three studies that examined impacts of carbon pricing on employment and wages found negative effects of a $20 carbon tax, which could be softened only to some extent by recycling of revenue. In terms of impacts on employment, the studies on Brazil and South Africa show a $20 carbon tax will result in opposite effects: an increase in unemployment in 2030 even with recycling of tax revenues for the South African case study, but a reduced level of unemployment from 6.86% in the reference scenario to 5.83% with a carbon tax in Brazil. Unemployment still is found, according to the model, but less than with the carbon tax, which has overall positive socio-economic implications. In the South African linked model by ERC, 1.06% fewer new jobs – for unskilled workers – were created relative to BAU by 2020. Higher energy costs as a result of the carbon tax would slow down the economy, limiting its ability to create new jobs. This would be a significant obstacle to finding political support. The MEG4C model used for Colombia does not yet not allow for analysis of changes in employment as such, but did find wages decreased by a modest 0.09% relative to BAU in 2020, for a $20 carbon tax and equivalent carbon cap.

In eSAGE, used by the South African team, households are disaggregated into income deciles and this makes it possible to analyse the impact of the carbon tax on poor and rich households. The ERC study found that the relative reduction in per capita consumption growth rates of poor households would be slightly lower than those of rich households, with decreases of 0.21% and 0.24% below BAU in 2040 respectively. Further analysis of moving the unemployed into employment is needed to confirm the robustness of these results – as well as other instruments for recycling.

To get a full understanding of the socio-economic implications of carbon pricing, both the tax and revenue streams should be considered. The ERC, COPPE and UniAndes-DNP teams, using various mechanisms, included recycling of revenue. The UniAndes-DNP team further considered a carbon tax also without transfers, but found little impact on GDP growth; their explanation for this result is that the macroeconomic effects of such transfers are seen in the long run.

The COPPE team explored various means of recycling revenue – through reduction of public debt (assumed in results in Table 4), or reduction in payroll taxes; or through 'green cheques' (Wills 2013; Wills et al. 2014a). The latter, which implies transfers to households, could use carbon revenue to increase direct transfers in Brazil, which have been important in social programmes such as *Bolsa Familia.*

ERC analysis considered recycling carbon tax revenues through the reduction of sales taxes and found that they would not have any significant redistributive impact on household incomes. It should be noted that the mechanism is reduction on all goods, not particularly targeted at those consumed by poor household. A targeted reduction in tax or other recycling mechanisms might have a different effect.

4.2 Implications of diverse mitigation actions

For fuller details of the mitigation actions analysed by the different teams, the reader is referred to their working papers (Benavides et al. 2014; Delgado et al. 2014b; Merven et al. 2014; Vasquez Baos et al. 2014; Wills et al. 2014a).

4.2.1 Law for non-conventional renewable energy in Chile

Chile has a law mandating that 20% of energy sales must be provided from NCRE sources by 2025. The UCh-PUC researchers evaluated a mitigation action that would further increase NCRE to 25% by 2030 (25/30) and 30% by 2030 (30/30). The results reported in the working paper include not only emission reductions and costs, but also a breakdown of Opex and Capex, marginal abatement cost and impacts on the electricity price.

Table 5: Evaluation on increased renewable energy in Chile

Indicator	25/30	30/30
Δ OPEX (MM US$)	-34.8	-225.2
Δ INCOME TAX (MM US$)	0.0	0.0
Δ CAPEX (MM US$)	550.5	1431.3
Total Δ Emission (MM tCO2e)	-19.9	-33.3
Average ΔAnnual Emission (MM tCO2e)	-1.4	-2.4
Abatement Cost (US$/tCO2)	99.5	150.7
Δ Electricity Price (US$/MWh)	1.0	2.4

Source: Benavides et al. (2014)

Table 5 shows the full results. What is notable is that the relative emission reductions of the 25/30 case are at a similar scale to those $10/tCO$_2$e carbon tax case, and the 30/30 case reduces about as much relative to BAU as a $20 /tCO$_2$e carbon tax. However, increasing shares of NCRE has a much lower impact on electricity price (at $10, the electricity price increase ranged from $3.9–4.4 / MWh; at $20, 8.3–9.6). Correspondingly, the impact on GDP of these scenarios is lower than that of the carbon taxes with similar emission reductions. According to the analysis by researchers in Chile, mitigation actions on renewable energy have a *lower* increase in electricity prices (and GDP impact) than carbon taxes with comparable emission reductions.

4.2.2 Renewable portfolio and industrial electricity program in Colombia

Researchers from UniAndes in Colombia also analysed a renewable portfolio standard. It assumes that industrial biomass cogeneration, small hydro plants, geothermal plants and small wind farms (< 50 MW capacity) are installed from 2015. The second energy programme consists of the substitution of fossil fuels in the industrial heat and steam processes by electricity. The results reported in the working paper (Delgado et al. 2014b) show that these two energy programmes together achieve a similar mitigation outcome as a carbon tax of $20 per ton CO$_2$. The emissions *pathway* differs, however, with the energy programmes increasing abatement, while carbon pricing is variable. The cumulative emissions reductions from the energy programmes do not rise, for which the UniAndes teams offers the explanation that some new facilities may replace installed hydro-electric capacity. The impacts on GDP between the energy programmes and carbon taxes were found to be very similar, comparable to a $10 carbon tax without recycling, or $20 with recycling of revenue. The two energy programmes also have a negative impact on wages, though at a lower magnitude than the impact on GDP (Delgado et al. 2014b).

4.2.3 Renewable energy in South Africa

The ERC team analysed mitigation actions supplying electricity through RE. In the reference scenario, no carbon tax was imposed, and only a small share of electricity came from renewable energy (< 1%), and about 5% from nuclear power in the base year. Coal-fired electricity declines from 90% in the base year to 83% in 2040 in the reference scenario. Solar PV makes up 5% of the share in 2040, and gas 4% in 2040.

The mitigation actions assume that shares of centralised RE grow to 20% by 2030 and 30% by 2040 in the RE programme 1 scenario and 30% by 2030 and 40% by 2040 in RE programme 2; that is, significantly above the reference case. Conservative and optimistic learning rates for the investment cost of renewable energy technologies were considered. Emissions reductions for the RE programme 1 and 2 were about 19% and 28% respectively, with conservative learning rates. Results indicate that the more aggressive renewable programme will have a more negative impact on GDP, relative to the reference scenario. GDP would be 1.46% less; relative to the BAU in 2040 for the RE programme 1 scenario and 1.85% less for the RE programme 2, with conservative learning rates for RE technologies. This could be due to increased electricity prices leading to higher costs of production for firms, thereby slowing down the economy. The services sector would have the largest drop in its contribution to overall GDP, compared to industry and agriculture. Losses in the industrial sector would mostly be from mining, petroleum products, chemicals, metals and construction. There would be significant increases in the electricity sector's contribution to GDP. Lower economic growth with the RE programme 2 would mean that fewer jobs (–3.87%) would be created compared to RE programme 1 scenario (–2.47%) by 2040, relative to BAU. This could be due to these RE programmes lowering employment in services and other industries such as mining and manufacturing, which are major employers in the South African economy. The RE programme 2 would also have a more negative effect on welfare, with per capita consumption of all households being 3.62% less relative to BAU in 2040, compared to being 2.57% less for RE programme 1, with conservative learning rates. The impact on household welfare would also be less negative with more optimistic learning rates for the respective scenarios.

4.2.4 Heavy industry in Brazil

A detailed analysis was undertaken for six industrial sectors in Brazil (paper, cement, steel, aluminium – and other nonferrous –, chemical and mining) and for oil-refining activities. Each sector shows the same behaviour in response to increasing levels of carbon price: (i) for small carbon prices, global energy efficiency gains are triggered and quickly reach an asymptote; (ii) for medium carbon prices there is a substitution between fossil fuel and renewable biomass.
Within this framework, the model analysed how to recycle the revenues from the carbon policy, whether it is a carbon tax or a cap and trade scheme, and the macroeconomic impacts. Three different types of carbon revenue recycling were considered, as reported in Table 3 above.

A range of carbon taxes was considered, varying from R$0–200 /t$CO_2$ ($0–50), under the three different types of carbon revenue distribution. With reduced public debt, GDP is greater than with reduced payroll taxes, for all price levels; payroll tax recycling shows consistently higher GDP than transfers to households, when compared with the same level of carbon tax.

A sensitivity analysis was conducted to confirm that modelling the recycling scheme through reduced payroll taxes shows smaller impacts on the economy. The economic reasons for this are that reduced payroll tax stimulates the creation of new jobs, and thus increases the income and consumption of households, reducing the recessive impact of the carbon tax. It is also important to note that there is a special range of the carbon tax (approximately 0–10 / t CO_2 (R$0–50)) which – with recycling via reduced payroll taxes – finds that a double dividend is possible, according to Wills (2013).

4.2.5 Agroforestry in Peru

The implications for socio-economic analysis of mitigation were built into the approach taken by IIAP, with agroforestry being the mitigation action. Key conclusions from this analysis (in addition to those in section 3.3) include important socio-economic implications. The IIAP study illustrated that there is an opportunity cost to preserving trees for a longer period; an approach seeking carbon credit would find only 15 years as a financially optimal period. Higher CER prices than currently observed would be needed. In the current context, small-scale projects would not be attractive, nor would regional governments see value in investing in agroforestry. However, the IIAP study emphasises the broader considerations. Carbon pricing is not the only mitigation plan but, in parallel, approaches that build the potential for export earning in the long-term need to complement short-term income. The social pressures on farmers to cut trees need to be understood as part of the mitigation strategy. A public-private partnership, combining investment by regional governments in agroforestry with (hopefully higher in future) CER prices is worth further consideration (Vasquez Baos et al. 2014).

5 CONCLUSIONS AND FURTHER WORK

Policy-makers in developing countries are concerned with charting the development paths of their economy and society. Providing information on the potential socio-economic benefits of a transition to a low-carbon society requires improved tools to deliver good information for decision-making. This research report has brought together the main findings from five research teams – COPPE in Brazil, UniAndes-DNP in Colombia, UCh-PUC in Chile, Instituto de Investigación de la Amazonía Peruana in Peru and the Energy Research Centre in South Africa.

The approaches to linking sectoral and economy-wide models provided several learnings on methodological issues. Four of the five research teams addressed the complex challenge of linking energy sector models (or at least electricity) to economy-wide ones. The linking of forestry models poses even greater challenges. IIAP did not find sectoral models that were comprehensive, and chose instead to compare results from an econometric model – calibrated for Peru and including agroforestry – to CER prices. No single approach is preferred: they have emerged in response to policy questions and particular circumstances for each team.

Various approaches were used to integrate sectors in economy-wide models; for instance hybrid accounts in IMACLIM, and automated exchange via GAMS between a TIMES and CGE model. A common challenge is the level of disaggregation, with economy-wide models, for example, commonly representing electricity as a single good, while energy sector models disaggregate by fuel (and technology). The methodological lesson, based on these studies, is that neither hard- nor soft-linking is better, but rather that both have advantages and limitations.

The five research teams took different approaches to the treatment of time, from one-shot, to sequential and dynamic approaches. Methodologically, the most important matter is consistency, and clarity on which of two (or more) models produces time-series. Sequential and dynamic approaches seem appropriate to questions of development and climate, since decision-makers need to understand how both economies and emissions evolve over time.

The four research teams that applied carbon prices of $10, $20 and $ 50 used different modelling frameworks, and different policy instruments might be pursued in their countries. All reductions are relative to a reference or business-as-usual case in 2020, except for Brazil (2030). Reductions in emissions were found to be highest in the UCh-PUC study of Chile, up to 21% at $50 / tonne CO_2-eq, though only applied to the electricity sector. The UniAndes-DNP study showed less than 6% relative reduction in GHG emissions at this tax level; ERC's implementation of a carbon tax in their modelling up to around 3% at most; and COPPE's analysis in IMACLIM-Brazil up to 12%. The report also noted fairly smooth increases in ERC and COPPE studies; contrasted with inflection points in the UniAndes-DNP and UCh-PUC results. These are not final or definitive findings on possible emission reductions in the countries, but do illustrate the mitigation outcome of carbon pricing. Where only the electricity sector has been linked, further work is needed in linking the rest of the energy sector and the other economic sectors in the model in order to allow for these sectors to respond to carbon taxes through fuel switching where possible. Such an extension would not cover the entire economy, but all of the energy economy and thereby most emissions.

Based on the work by the modelling teams, it appears that significant reduction can be achieved with a $20 carbon tax, with GDP losses around 0.1% in South Africa as modelled by ERC, 0.5% for in the UniAndes-DNP analysis of Colombia and 2% in the Chilean power sector as modelled by UCh-PUC, but a 0.6% increase in Brazil's GDP according to COPPE analysis. The results in Table 4 show that a tax of $20 per ton CO_2-eq reduces economic output by less than 2%, comparing GDP in the tax case to BAU, for all the countries studied – and in one case had positive socio-economic implications (Wills 2013). It should be noted that the results might also be due to differences in assumed carbon pricing mechanisms, recycling of revenue, and models chosen. These results provide examples of the information that can be generated from linked models, to understand better the socio-economic implications of mitigation and related policy questions.

The two studies that examined impacts of carbon pricing on employment and wages found negative effects of a $20 carbon tax, which could be softened only to some extent by recycling of revenue. In the UniAndes-DNP analysis of a $20 tax in Colombia, wages decreased very slightly (0.09%), with emission reductions of about 0.5% relative to BAU). The ERC study showed 1% job losses at $20, all for unskilled workers. This would be a significant obstacle to implementing the policy; however, it should be noted that full employment is assumed for skilled labour, so further work should replicate these results, and consider shifts of unemployed into employment. The disaggregation of households into declines in the eSAGE model allows analysis of impacts on poor and rich households The impact of carbon taxes was found to affect rich household slightly more than poor households. Household consumption, the chosen option for recycling of revenue, via a sales tax, does not have as significant a re-distributional impact on household incomes as expected. Further analysis of moving unemployed into employment is needed to confirm the robustness of these results, as well as other instruments for recycling.

The analysis by COPPE of a $20 carbon tax in Brazil indicates relative emissions reduce by 10%, with a small increase of relative GDP by 0.6% in 2030. The price index increases by 3.2% in 2030. However, an 8.5% reduction in public debt can be achieved, with appropriate recycling (reducing payroll taxes). Thus emissions reductions are possible with a small increase in GDP, some price increases, a positive in reduction of public debt and reduced unemployment. Overall, the socio-economic implications of these findings for Brazil (Wills 2013; Wills et al. 2014a) are the most positive across the studies reported in this joint paper.

In the Chilean electricity sector, reductions start at lower levels (3.5%), but rise sharply between $20 and $50, reaching just over 20% reduction in emissions relative to BAU. The Chilean case study thus suggests that the carbon tax may have a higher impact on electricity prices than a CO_2 tax *with emissions caps* reaching the same emissions reductions.

The Colombian team found that although recycling carbon taxes through transferring revenues to household reduced the impact on GDP, it was not enough to prevent the negative effect on GDP. In other words, there is no 'free lunch' in mitigating GHG emissions with a carbon tax. Finally, the carbon tax (with or without recycling), the carbon cap, fixing a renewable portfolio and imposing electricity for industry, all have a small impact on GDP levels – less than 1% with respect BAU.

The Peruvian study illustrates that non-price factor are sometimes more important, as with their finding for investment in agroforestry systems that also sequester carbon. The IIAP study of agroforestry in Peru considered the opportunity cost of preserving trees more than 15 years. Higher prices of CERs would be needed to extend this to 30 years. With current prices and governance, small-scale CDM projects would not be attractive, nor would regional governments see value in investing in agroforestry. Rather than pricing carbon, IIAP recommends a public-private partnership; combining investment by regional governments in agroforestry with (hopefully higher in future) CER prices is worth further consideration.

Many mitigation actions were examined by three research teams (Benavides et al. 2014; Delgado et al. 2014b; Merven et al. 2014); here the results for those including renewable energy (RE) are compared.

The ERC's analysis of 20% (30% in the second scenario) of electricity generated from RE by 2030 and 30% (40%) by 2040 showed greater emission reductions than a carbon tax. The two RE scenarios reduced emissions 19% and 28% below BAU; whereas a $20 carbon tax reduced 2% in relative terms. However, GDP losses were greater (to a lesser extent with more optimistic learning rates for investment costs of RE). The decrease of the industrial sector's contribution to GDP outweighs an increase in the electricity sector's contribution, due to lower economic growth, and hence also reducing employment (Merven et al. 2014).

The UCh-PUC found that a further increase of non-conventional RE to 25% by 2030 (25/30) reduces emissions to a similar degree as a $10 / t CO_2-eq tax (and 30/30 is comparable to $20 tax). The mitigation action with NCRE has a *lower* increase in electricity prices (and GDP impact) than carbon taxes with comparable emission reductions. It seems the carbon tax in Chilean electricity sector is not ideal for electricity prices, and investment in more renewables – or indeed emissions limits – might be more optimal (Benavides et al. 2014).

The UniAndes-DNP team similarly found that, in Colombia, a renewable portfolio and industrial electricity programmes would achieve a similar mitigation outcome as a $20 carbon tax. GDP losses between these energy programmes were roughly similar to the carbon tax – without recycling at $10, with recycling at $20. The findings on socio-economic implications of mitigation using linked sectoral/economy-wide models are significant both in methodological development and substantive results. Given the methodological advances made, further work is needed to improve the analysis, test results for robustness and provide credible information to decision-makers (Delgado et al. 2014b).

The research teams have identified a number of areas for further work. Integration of AFOLU sectors is less mature than for energy (or at least electricity) sectors. The COPPE team is planning further disaggregation in the land use sector in future, linking with the Brazilian Land Use Model (BLUM) model run by ICONE. This requires disaggregation of land-use in the CGE model; and further work on a hard-link, combining IMACLIM, BLUM, MESSAGE and LEAP, as proposed by Wills (2013); the COPPE team continues to work collaboratively with ICONE, CIRED and ERC on this integration. Wills, Lefevre and Grotera (2014b) developed a new version of IMACLIM for Brazil dividing households in six income classes, which allow the model to provide results on inequalities (Gini coefficient for each mitigation scenario), and more precise results on the distributional effects of transfers from the government to poor families. This can be complemented by building on the IIAP approach of combining biometric and econometric analysis. Further work is needed to extend the analysis from regional to national level, and integrate other mechanisms (such as private-public options).

The four research teams focusing on energy started with the electricity sector. Moving from electricity to full energy models linked to economy-wide ones is part of the research agenda. The UniAndes team intends to disaggregate the energy sector in MEG4C (CGE, working with DNP) and the industrial sector in Colombian Markal model. The ERC team aims to integrate other energy sub-sectors to allow fuel-switching and better appreciation of energy efficiency. This will also allow for the attainment of more robust results on the impact on emissions for the economy as a whole. Further analysis of distributed generation of renewable energy is another aspect of further work. ERC also plans to work on more rigorous analysis of uncertainty. The UniAndes team plan to take into account transaction costs in the carbon tax and carbon cap scenarios, in future work.

Carbon pricing (whether through tax or trade) can generate revenues. Including the expenditure of revenue is represented as recycling of revenue in modelling. This is an area that has particular priority, as the socio-economic results depend not only on whether recycling is included, but also what mechanisms are modelled. Mechanisms that improve the distributional impacts of carbon pricing – such as direct transfers to households – are an important area of further work.

Linking sectoral and economy-wide modelling to better understand the socio-economic implications of mitigation pushes the frontiers of knowledge. It has the potential to provide crucial information for decision-making on development and climate. The findings in this report are an important step forward, but – in the view of the authors – by no means the final word. Building modelling frameworks that can more fully implement a developmental approach is a long-term and ambitious research agenda. The next step may be to develop frameworks that can model different development pathways, aimed at multiple objectives, and account for the differences in emissions.

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