A Linked Emissions Trading Scheme under alternative scenarios: implications for Europe and Brazil

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ABSTRACT

The Paris Agreement has recently highlighted the importance of international cooperation through carbon pricing, as well as the need for support from developed and developing countries to tackle climate change. With Emissions Trading Schemes (ETS) emerging in developed and developing regions around the world, linking these systems may become a future option. This raises the question as to the appropriateness of bilateral ETS linkages between developed and developing regions. Based on discussions of carbon pricing in Brazil, this paper investigates the impact of a sectoral ETS covering electricity and energy-intensive sectors using a global economy-wide model, the EPPA6. Additionally, we simulate a link with a developed region, Europe, under five alternative ETS design scenarios. We find that a sectoral ETS linkage results, for both participants, in more significant emissions reductions, a technological substitution towards alternative energy, and losses in GDP and welfare where a stringent cap is imposed. The appropriate ETS design to seize mitigation opportunities cost-effectively for both regions includes a less stringent cap for Brazil, the introduction of revenue recycling for the production of alternative energy and, in the long-term, the banking of permits. As Brazil presents an importer profile of allowances in the short run, and becomes an exporter to Europe by 2050, this design would concurrently provide emissions reductions and, to a certain extent, improve the cost effectiveness of the ETS linkage in the long-term.

KEY WORDS: Emissions Trading Scheme (ETS), linkage, EU ETS, Brazil, EPPA6

JEL classification: D58, Q48, Q58

1. INTRODUCTION

Linkage of national climate policies is increasingly gaining relevance in the climate policy architecture, especially after the provisions introduced by the Paris Agreement. Article 6 of the agreement provides the foundation for carbon pricing at international level to comply with Nationally Determined Contributions (NDCs). Although not explicitly mentioned as

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"Emissions Trading", the agreement envisages the use of "internationally transferred mitigation outcomes" to achieve significant progress on emissions mitigation.

In light of that, developing countries are encouraged to also take action with the support of developed countries. In the past, developing countries had been involved in climate change mitigation through flexibility mechanisms, as hosts of Clean Development Mechanism (CDM)[2] projects, or in some cases, by committing to voluntary reduce emissions. Recently, a Chinese Emissions Trading Scheme (ETS) has been launched.

Carbon trading is likely to become even more common post-2020, as further countries plan, or at least investigate the potential for ETS adoption[3]. As a result, linkages have the potential to develop among participants in the future.

To date, a small number of the active national and subnational carbon markets are involved in, or are open to the concept of, ETS linkages. Examples include the California, Quebec and Ontario link (the Western Climate Initiative, WCI) and the Regional Greenhouse Gas Initiative (RGGI) in the northeast of the USA. The European Union Emissions Trading Scheme (EU ETS), the largest and most consolidated system in the world, displays willingness to link with other compatible systems, which means other ETS systems with similar environmental integrity and system architecture could potentially link. There is currently a Norway-EU linkage, which also regulates the aviation sector. Literature in this regard underlines potential opportunities from the use of market-based instruments in a framework of international cooperation, since aggregate emissions reductions are achieved at a lower cost (Bodansky *et al.*, 2014, Burtraw *et al.*, 2013).

In this research, linking occurs exclusively through cap-and-trade schemes set up at the country-level. Under this approach, the marginal abatement costs are equalised among regulated jurisdictions so that there are greater abatement options available. As a consequence, the system with a higher pre-link carbon price benefits as it can buy cheaper allowances, whereas the system with a lower pre-link price gains as a result of higher abatement and the sale of allowances. Besides contributing to greater cost-efficiency, linking ETS systems can increase market liquidity and potentially lower the risk of carbon leakage.

[2] In the Kyoto Protocol, a number of Certified Emissions Reductions (CERs) were issued for each project approved, mostly implemented in China, India or Brazil. The CERs generated by investing in these projects could be traded in the existing carbon markets of developed countries. This was the case for the EUETS.

[3] Mexico, Egypt and Vietnam have announced their plans to implement a national ETS that could be linked to others in the mid-term to long-term.

Some aspects need to be considered when deciding on linking, for instance, existing differences on the level of ambition, the ETS design and regulatory rules, potential domestic distributional impacts, and political support. Rather than enhance environmental effectiveness, a bilateral link where the relative stringency of targets or the design features of the ETS differ among participants, may impair the climate policy. Although engaging in linkage demonstrates the effort to establish comparable caps and attract political support, it can also signalise that lower ambition is acceptable or that there is a loss of national regulatory control. Furthermore, distributional impacts associated with financial transfers from trading may be an additional issue.

Several studies have been carried out in order to evaluate linking with the EU ETS, including the possibility of linking with non-EU schemes such as South Korea, China, Australia and California. Some of these studies investigated the effects of sectoral ETS linkage under different circumstances. For instance, Gavard *et al* (2016) modelled a sectoral ETS on electricity and energy-intensive industries in the EU, the US and China, simulating autarky and linkage scenarios. Hübler *et al.* (2014) assessed a Chinese ETS regulating energy-intensive industries, electricity, heat, petroleum and coal products considering a potential cooperation with the EU ETS. Results from these studies showed an increased adoption of low carbon technologies, a lower international leakage and generally, a greater degree of acceptance from developing countries to participate in the carbon market set by developed countries.

The framework introduced as part of this paper considers linkage implications of a hypothetical Brazilian ETS with a similar sectoral coverage to the aforementioned studies. Among developing countries, Brazil has taken on a pioneering position when it comes to commitments to mitigate climate change. With approximately 3% of global emissions in 2014, Brazil agreed to reduce emissions by 37% and 43% of 2005 levels by 2025 and 2030 respectively, in addition to a commitment to stop illegal deforestation.

Notwithstanding the relatively low carbon intensity of the energy mix, Brazil still relies on the production and consumption of fossil fuels, which has the potential to hinder a genuine carbon mitigation towards sustainable levels. Therefore, climate policies aimed at energy-related sectors are required to help achieve national climate goals, as they correspond to approximately 36% of total emissions.

The Brazilian government has been supporting, in association with the World Bank - Partnership for Market Readiness (PMR), a comprehensive group of studies based on carbon pricing for the post-2020 period[4]. Despite that, Brazil has not yet defined or even decided on whether to implement a domestic ETS. However, the arrangements for market instruments in the Paris Agreement may encourage Brazil to design a carbon trading system. By taking the lead, Brazil may encounter new opportunities for climate cooperation with developed systems, with the EU ETS being a potential candidate. This is due to the fact the EU ETS displays a willingness to link with other compatible systems, which means that other ETS systems with a similar environmental integrity and system architecture could be a potential trading partner.

The implications of such proposals have to date not been investigated as carbon pricing and related linkages have just emerged as a reasonable alternative for developing countries. This is reflected by the late incorporation of climate issues into the Brazilian domestic agenda, that is, the secondary relevance given to environmental issues in light of other political national priorities. Additionally, it demonstrates that developing countries are envisioning financial opportunities from ETS systems. The expected benefits of accessing the market and joining a linkage are related to the exporter role developing countries would presumably assume (Somanathan, 2008).

In this context, this paper conducts a two-fold investigation and examines the proposed climate policy, that is, a linkage between the EU ETS - the largest and most consolidated system in the world - with a proposed non-EU scheme – a Brazilian ETS (Bra-ETS), using environmental (emissions and energy) and economic impacts as evaluation criteria. The study measures potential costs and benefits of implementing a sectoral ETS linkage, which exclusively regulates CO_2 emissions from energy intensive industries and the electricity sector under alternative scenarios; as well as verifying whether the EU ETS may serve as a model for the Bra ETS.

By employing a dynamic-recursive computable general equilibrium model of the global economy - the EPPA6, this study fills the existing gap in the literature, augmenting previous studies (Domingues *et al*., 2014; Feijó and Porto Jr., 2009; França, 2012; Gurgel, 2012; Gurgel and Paltsev, 2014; Henriques, 2010; Lucena *et al*., 2015; Rathmann, 2012; Silva and Gurgel, 2012; Wills and Lefvre, 2012).

The paper is organised in the following way. In Section 2, we introduce the EPPA6 model and an overview of the scenarios. Section 3 exhibits the main modelling results for the

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[4] The legal principle for implementing market-based mechanisms to emissions mitigation has been previously set up in the National Climate Change Plan (or PNMC in Portuguese) under Articles 4 and 6, even though there is a lack of detailed information on the market regulation.

proposed ETS linkage, in the light of different ETS design scenarios. In assessing if the evaluation criteria are achieved, the investigation provides suggestions on the most appropriate ETS features in case of climate coordination. Section 4 offers concluding remarks and policy implications.

2. MODELING FRAMEWORK

The analysis of this paper extends the Economic Projection and Policy Analysis (EPPA) model in its most recent version - EPPA6[5] (Chen *et al.*, 2015). The modeling is set up to represent a hybrid climate policy approach, with emphasis on sectoral ETS trading.

2.1. Characteristics of the EPPA model

The EPPA6 model is a dynamic-recursive computable general equilibrium (CGE) model developed by the MIT Joint Program on the Science and Policy of Global Change. The model was developed as a nonlinear complementarity problem in the General Algebraic Modelling System (GAMS) programming language (Brooke *et al.*, 1998), using the syntax of the MPSGE (Mathematical Programming System for General Equilibrium) algorithm developed by Rutherford (1999).

EPPA6 is solved for a sequence of global market equilibrium considering "myopic" expectations of economic actors that provides a representation of the global economy (Chen *et al.*, 2015). This assumption in EPPA means that current period investment, savings, and consumption decisions are made on the basis of prices in each 5 year period (Paltsev *et al.*, 2007). As a CGE model, EPPA6 can represent the global production and consumption of various sectors of each regional economy and the associated greenhouse gas emissions (GHG), being interconnected to other regions through international trade. Additionally, it is able to incorporate emissions constraints on regions, gases or sectors within different policy arrangements.

The model considers a long run simulation horizon (2010-2100). It is solved at 5 yearly intervals. By projecting scenarios of world economic development and emissions trends, it enables analysis of the economic impact of mitigation and energy policies as well as welfare and equity measures. It was adopted in this policy analysis to answer the questions posed with regard to the sectoral ETS applied in a hybrid framework, and thereafter, the international cooperation in the period 2020-2050.

[5] Free public version is available at: https://globalchange.mit.edu/research/research-tools/human-system-model/download .

In each of these periods, there are production functions in all sectors that describe the use of primary factors (capital, labour, and energy resources) and energy and intermediate inputs for producing goods and services for each country or region. The level of consumption is modelled through a representative agent[6] that seeks to maximise utility by choosing how to allocate its income from factor payments (wages, capital earnings, resource rents) across consumption or savings (Gurgel and Paltsev, 2014; Henry *et al*., 2015). The government is a passive entity, which finances government consumption, and transfers with revenue from taxes paid by households and producers. Deficits and surpluses generated return to consumers as lump sum transfers.

Production sectors transform primary factors and intermediate inputs into goods and services in order to maximise profits, given the available technology and market prices. Producers receive payment in return from supplying those products to domestic or foreign agents. Similar to other CGE models, EPPA6 uses nested Constant Elasticity of Substitution (CES) with several inputs in order to specify preferences and production technologies. International trade is accommodated via Armington assumption (Armington, 1969), with the exception of crude oil, being a homogeneous good. All markets reach a simultaneous equilibrium when zero-profit, market-clearing and income balance conditions are satisfied in the static part of the model.

The dynamics of the model are determined by exogenous factors (GDP projections for BAU growth, labor endowment growth, factor-augmented productivity growth, autonomous energy efficiency improvement (AEEI) and natural resources assets) and endogenous factors (savings, investment[7] and fossil fuel resource depletion) (Chen *et al.*, 2015).

This version is calibrated using the Global Trade Analysis Project Version 8 (GTAP 8) database, with a benchmark year of 2007 (Narayanan *et al*., 2012). The GTAP dataset comprises a detailed representation of national and regional input-output structure, which includes bilateral trade flows in goods and services, intermediate inputs among sectors and taxes or subsidies imposed by governments (Dimaranan and McDougall, 2006; Aguiar *et al*., 2016). In Table 1, data is aggregated into 18 regions, 14 sectors and 14 technologies for generating low carbon energy. EPPA6 also incorporates additional data sources on energy use

[6] EPPA6 accounts for three economic agents: consumers (households), producers and government. Households own primary factors, offer these to producers and receive income from the services provided (wages, capital earnings and resource rents).
[7] Savings and consumption are represented in the household's utility function by an aggregated Leontief approach.

(IEA, 2012), energy consumption (IEA, 2012), CO_2 emissions related to cement production (Boden *et al*., 2010) and CO_2 emissions related to land use change (Riahi *et al*., 2007).

Table 1

Aggregation of regions, sectors and backstop technologies in EPPA6

Regions	Sectors	"Backstop" Technologies and production factors
	Agriculture	
United States (USA)	Crops (CROP)	First generation biofuels (bio-fg)
Canada (CAN)	Livestock (LIVE)	Second generation biofuels (bio-oil)
Mexico (MEX)	Forestry (FORS)	Oil shale (synf-oil)
JAPAN (JPN)		Synthetic gas from coal (synf-gas)
Australia and New Zealand (ANZ)	*Non-Agriculture*	Hydrogen (h2)
Europe (EUR) [8]	Food production (FOOD)	Advanced nuclear (adv-nucl)
Eastern Europe (ROE)	Services (SERV)	IGCC w/ CCS (igcap)
Russia (RUS)	Energy-intensive (EINT)	NGCC (ngcc)
East Asia (ASI)	Other industry (OTHR)	NGCC w/ CCS (ngcap)
South Korea (KOR)	Transport (TRAN)	Wind (wind)
Indonesia (IDZ)	Ownership of Dwellings (DWE)	Bio-electricity (bioelec)
China (CHN)		Wind power combined with bio-electricity (windbio)
India (IND)	*Energy supply*	Wind power combined with gas-fired power (windgas)
Brazil (BRA)	Coal (COAL)	Solar generation (solar)
Africa (AFR)	Crude oil (OIL)	
Middle East (MES)	Refined oil (ROIL)	*Factors of production*
Latin America (LAM)	Gas (GAS)	Labor
Rest of Asia (REA)	Electricity (ELEC)	Capital
		Natural Resources
		Land

Source: Based on Chen *et al.* (2015).

Scenarios of climate policy are forecasted based on the model theoretical assumptions and are driven by economic growth, which in turn results from savings and investments as well as productivity improvement in labor, energy and land which are exogenously specified (Gurgel and Paltsev, 2014; Octaviano *et al*., 2016). The higher the growth in gross domestic product (GDP) and income levels, the greater the demand for goods produced by each sector. This ultimately leads to higher production costs, as these goods use finite natural resources in the production cycle.

A constraint on emissions alters the relative economics of technologies as advanced technologies become available cost-effectively and compete with traditional energy technologies on an economic basis. ETS simulations with EPPA6 have a solution in which the

[8] The European Union (EU-27) plus Croatia, Norway, Switzerland, Iceland and Liechtenstein.

least-cost abatement is achieved for each sector and type of emission, and prices are equilibrated if emissions trading is allowed.

In this case, as a result of limiting emissions, a shadow value of the applied constraint is calculated. This is interpreted as a price obtained under the potential permit market in the ETS. Modelling the proposed sectoral ETS required adjusting the model to allow sector-specific permits trading at international level. Further details on EPPA6 may be found in Chen *et al*. (2015).

2.2. Sectoral ETS and mitigation objectives

In earlier UNFCCC sessions, the main involvement developing countries had with carbon markets was through the Clean Development Mechanism (CDM), being project hosts without binding pledges. Conversely, in the Paris Agreement both developed and developing regions affirmed long-term mitigation goals.

Brazil has committed to reduce emissions by 37% and 43% of 2005 levels by 2025 and 2030 respectively. For modelling purposes, the mitigation target is projected to rise 2% per 5-year period up to 2050, when a 50% reduction of the 2005 emission levels is achieved in the Brazilian ETS and non-ETS sectors. The only disregarded sectors in the mitigation applied target are land use change and deforestation. Given that these sectors represent a relatively high share of total Brazilian emissions, controlling emissions from those sectors would automatically prevent other sectors from broadening mitigation effort to comply with national climate targets.

Although there is no explicit reference to any intention of setting up a market-based policy, irrespective of whether a cap-and-trade system or a carbon tax, the PNMC does allow the use of these instruments. This paper therefore proposes an ETS design for Brazil which could facilitate linking with other schemes. The ETS design was defined to mimic the EU ETS, serving as a realistic prototype for other planned systems.

The restrictions on emissions represent the regulation stringency. The same sectoral and emissions coverage as the EU ETS are applied to Brazil so that both systems regulate electricity generation (ELEC) and energy intensive industry sectors (EINT), and only CO_2 emissions are subject to the absolute cap. The ETS sectors are assumed to be allocating tradable allowances between them[9]. There is no specified limit on the amount of sectoral permits that can be traded.

For the European system we applied the emission reduction linear factor of 1.74% per annum from 2013-2020 and 2.2% from 2021-2030 as already specified for the EU ETS[10]. From 2030 onwards the mitigation target is assumed to increase by 1% per year until it reaches a target representing a 73% reduction of 2005 levels by 2050. In the modelling exercise no distinction is made on the EU ETS phases, the bank of unused oversupply of carbon allowances or the existence of the New Entrants Reserve (NER 300 programme).

Additionally, a supplementary policy is included by means of a hypothetical (endogenous) carbon tax on the remaining non-ETS sectors. It was included to mimic other domestic abatement measures and to avoid carbon leakage from ETS to non-ETS sectors. This tax prevents carbon emissions in those sectors from exceeding BAU levels and reflects the aggregate marginal abatement costs (MACs) of these sectors. The tax is generated by the model in order to induce each sector to cut emissions by the same national percentage target.

All other regions in the model follow the same hybrid market approach domestically, with the CO_2 constraints being in line with their pledges under the Paris Agreement from 2020-2030, based on the information available on the UNFCCC website[11]. From 2030 onwards, targets were estimated following the same average mitigation effort as officially committed for the Paris Agreement period.

The approach of imposing a sectoral carbon tax on non ETS sectors may not be realistic, but an ETS alone is unlikely to allow a country to achieve its Paris emissions reduction targets. The sectoral carbon tax captures in a simplified way the several alternative sectoral measures a country may use to mitigate emissions, given the current limitations in bringing all sectors into an ETS system.

[9] EPPA6 model assumes GHG permits are allocated as an endowment to the representative agent, who sell permits to sectors and consumers. It may be though as an auction mechanism, where revenue accrues as a lump sum transfer to families.

[10] The limitation of using the EU ETS targets is that we could not incorporate the EU commitment to reduce emissions of 40% of 1990 levels by 2030 in the model. Instead, the EU achieves approximately 38% of 2005 levels.

[11] Since EPPA6 is aggregated into regions and pledges are determined at a national level, the mitigation goals were defined taking into consideration the most representative country in the region where data is available or the average of the pledges committed.

2.3. Scenarios

The EU ETS and the proposed BRA ETS are considered from three perspectives: the Business as Usual scenario (BAU) without any mitigation policy, a domestic ETS, and a linked ETS. In addition, we simulated five different scenarios to compare the effects of linking a Brazilian sectoral ETS to the EU ETS. In all trading scenarios, allowances flow from the region with the cheapest abatement cost, thereby equalising prices and guaranteeing a cost-effective policy.

Scenarios are summarised in Table 2 and include: i) a linked system with no flexibility arrangements, (i.e. no banking or revenue recycling); ii) a link considering a lower ambition for Brazil based on the same framework[12]; iii) a linkage in which banking of allowances over periods is possible (it permits to shift reductions to a lower-cost time period)[13]; iv) a link with revenue recycled to the production of renewable energy for Brazil[14]; and finally, v) a linked system without active market-based instruments in other regions and no flexibility rule applied to Brazil and Europe.

Table 2

Scenarios summary

Scenarios	**Carbon constraint on emissions from regulated sectors**	**Hybrid approach in other regions (without trading)**
No-policy	no mitigation policy applied	No
Bra-ETS	a sectoral Brazilian ETS	Yes
EU-ETS	a sectoral European ETS	Yes
Bra-EU-Trade	a Bra-EU link, no banking, no revenue recycling	Yes
Bra-EU-Ambition	a Bra-EU link with reduced mitigation ambition for Brazil, no banking, no revenue recycling	Yes
Bra-EU-Banking	a Bra-EU link that allows only banking	Yes

[12] To calculate a reduced mitigation for Brazil we considered that emissions from deforestation are zero, as promised in the NDC. Therefore, we reduced the target by the same percentage as the share of deforestation in total emissions, that is, 27.5%.

[13] To allow the banking of allowances to be included in the ETS design, the carbon price trajectory was controlled in order to reproduce a price that increases at a constant real interest rate. This is in accordance with the Hotelling model for the economics of exhaustible resources (Hotelling, 1931). The EPPA6 model considers the interest rate of long term equilibrium to be 4% per year.

[14] Revenue recycling is introduced into the model in order to generate a reduction of taxes, which is similar to providing a subsidy. The aim is to induce a wider adoption of low-carbon technologies by making the final price of this energy artificially less expensive.

Bra-EU-Rev-RW	a Bra- EU link with revenue recycled into the production of renewables in Brazil	Yes
Bra-EU-Only	a Bra-EU link, no banking, no revenue recycling	No

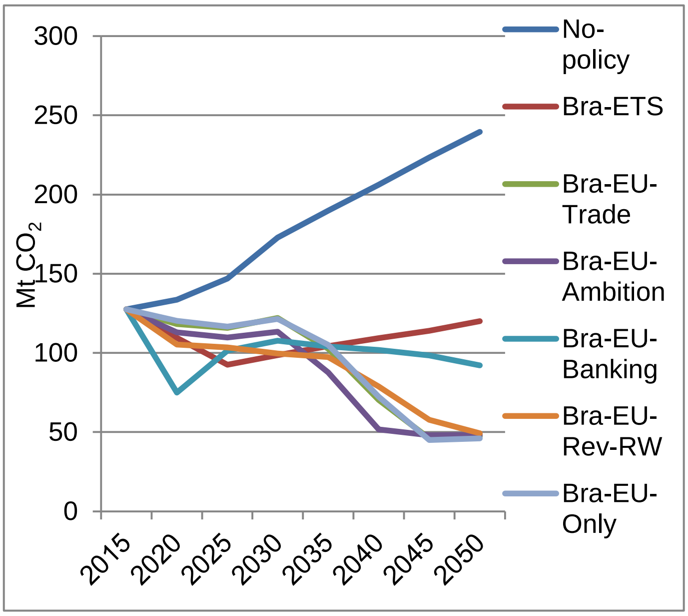
3. RESULTS

The findings presented in this section are dependent on the core assumptions we made in Section 2.2. Results of the EPPA6 simulations for the scenarios described in the previous section reflect the design of the market mechanisms in which the linkage architecture takes place.

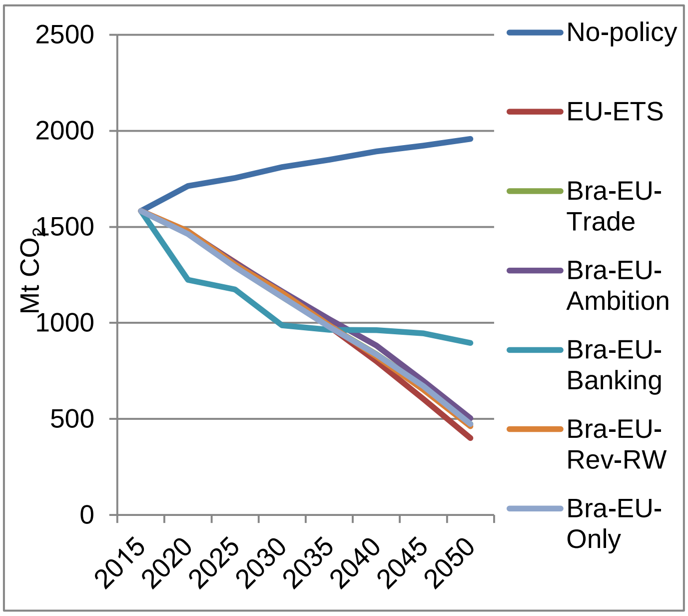
Emissions from the sectoral ETS are presented in Figure 1 and carbon prices are displayed in Figure 2. Overall abatement costs of the climate policy for regulated sectors are affected by the carbon price, whether in autarky or in a linked-ETS situation. The difference is that sectoral trading leads to a carbon price equalisation between the jurisdictions involved, eliminating marginal abatement cost divergences. In the absence of an international carbon trading system (Bra-ETS scenario), emissions from power and energy-intensive industries in Brazil are 98.6 and 120 million tonnes in 2030 and 2050, respectively. This is equivalent to 74.3 and 119.6 million tonnes less than NO-POLICY emissions for the same period, with a corresponding CO_2 price of US\$202.4/tCO_2 in 2030 and US\$304.9/tCO_2 in 2050.

Figure 1

CO_2 emissions from the sectoral ETS in Brazil and Europe



(a) Brazil



(b) Europe

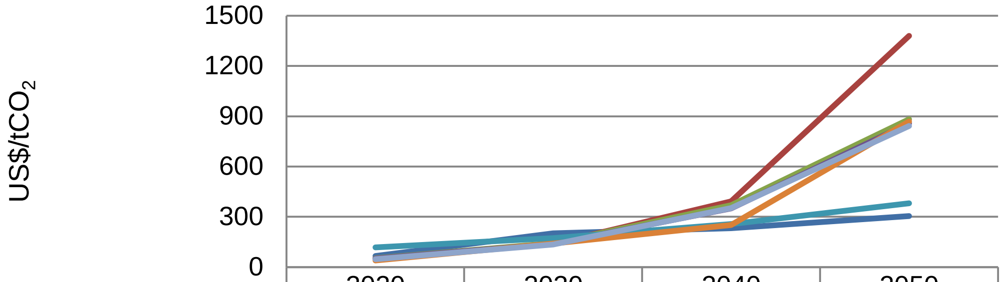
Under the ETS constraint and without climate cooperation, sectoral emissions in the EU ETS are 1.16 and 0.4 billion tons of CO_2 in 2030 and 2050. In this scenario, carbon permits cost US$139.3/t$CO_2$ and US$1379.7/t$CO_2$, respectively. This ETS price is endogenously derived and strongly impacted by the model representation regarding macroeconomic assumptions, availability and costs of backstop technologies, uncertainties and other modelling characterisation. Mitigation in the long-term would, indeed, require an increasing carbon price to discourage intensive reliance on carbon-based energy sources (Edenhofer *et al*., 2009). Previous projections using different models and ETS design estimate a carbon price ranging between 120 and 1200 €/tCO2 in 2050 to meet the climate goals (Peñasco and Del Río, 2015; EU, 2016).

If trading is allowed between Brazil and Europe, the carbon price is equalised across the two systems at US$143.4/t$CO_2$ and US$141.5/t$CO_2$ in 2030 of the Bra-EU-Trade and Bra-EU-Rev-RW scenarios. These linking prices are almost pegged to the EU's autarky price of US$139.3/t$CO_2$ in 2030, given its sheer size relative to Brazil's (in terms of volume of covered emissions), thereby making marginal abatement costs not much lower than in Europe. Brazilian sectoral emissions in the aforementioned linkages are 122 and 99.7 million tonnes in the Bra-EU-Trade and Bra-EU-Rev-RW scenarios, and those from the EU ETS are 1135.3 and 1157.6 million tonnes in 2030, a reduction of 37.3% and 36.1% in BAU emissions, respectively.

Linking Bra-ETS with the EU-ETS makes a tonne of CO_2 cheaper to Brazil than obtaining it at domestic level by 2030. For instance, the minimum cost of carbon possible is achieved when only Brazil and Europe commit to mitigation (US$135.1/t$CO_2$) or either if Brazilian ambition is lowered (US$139.2/t$CO_2$). From 2035 onwards, carbon prices in a linked situation are higher for Europe relative to autarky. This is understandable as the carbon price in the EU-ETS case is greater than in all Bra-EU scenarios.

Figure 2

CO_2 prices under different scenarios



	2020	2030	2040	2050
Bra-ETS	67.0	202.4	232.6	304.9
EU-ETS	51.7	139.3	391.4	1379.7
Bra-EU-Trade	53.6	143.4	369.5	882.0
Bra-EU-Ambition	50.9	139.2	350.7	857.2
Bra-EU-Banking	117.3	173.6	257.0	380.4
Bra-EU-Rev-RW	39.7	141.5	250.5	869.6
Bra-EU-Only	47.5	135.1	353.0	841.7

To date, carbon prices have remained persistently low in the EU ETS since it was launched, roughly hovering between €4 and €10 euros during the current third trading phase[15]. This price is considered to be very low to promote significant incentive for polluters to undertake necessary investments in low-carbon technologies, to drive low-carbon innovation but also to cost-effectively achieve proposed mitigation, particularly in a context of persistent supply imbalance of carbon permits [16](Kollenberg and Taschini, 2016).

Further, these low carbon prices are far below most estimates of the social costs of carbon (Anthoff and Tol, 2011; Foley *et al.*, 2013) as well not being at a meaningful level to drive deep decarbonisation. As such, sectoral emission reductions and resulting carbon prices in this simulation are coherent with the intended internalisation of the costs of pollution, although a rise in the EU's carbon price is uncertain to predict, at least in the short term.

From the climate perspective, aggregate emission reductions are a major indicator of environmental benefits. In a combined framework, Brazil and Europe account for a significant

[15] In general, this continuous downtrend has ensued from the economic recession and renewables-promoting policies that contributed to a decrease in permit demand as well as low capacity of the system to respond to changes in economic circumstances (Kollenberg and Taschini, 2016; Grosjean *et al.*, 2014; Ellerman *et al.*, 2015).

[16] After incurring volatile prices and windfall profits, regulators started reviewing the system so as to strengthen the functioning of the EU ETS, for example, by addressing the oversupply problem. For that, EU regulators proposed a "back loading", that is, a reduction on the number of allowances available in the market through near-term auctions, whereas the quantity removed is later on reintroduced. Another reform incorporated was the implementation of the Market Stability Reserve (MSR) in an attempt to create a system more resilient to supply-demand imbalances.

share of carbon emitted globally, i.e. 3% of total emissions and 5.4% of power sector and energy intensive industry emissions. From the simulations, the joint emission reductions in the linked system are greater if potential revenues are recycled back to the production of renewables in Brazil, particularly in the long term, representing a 48% reduction compared to the No-Policy scenario. The advantage of this scenario is that distributional implications from the ETS implementation in Brazil can be, to a certain extent, addressed or at least partially compensated.

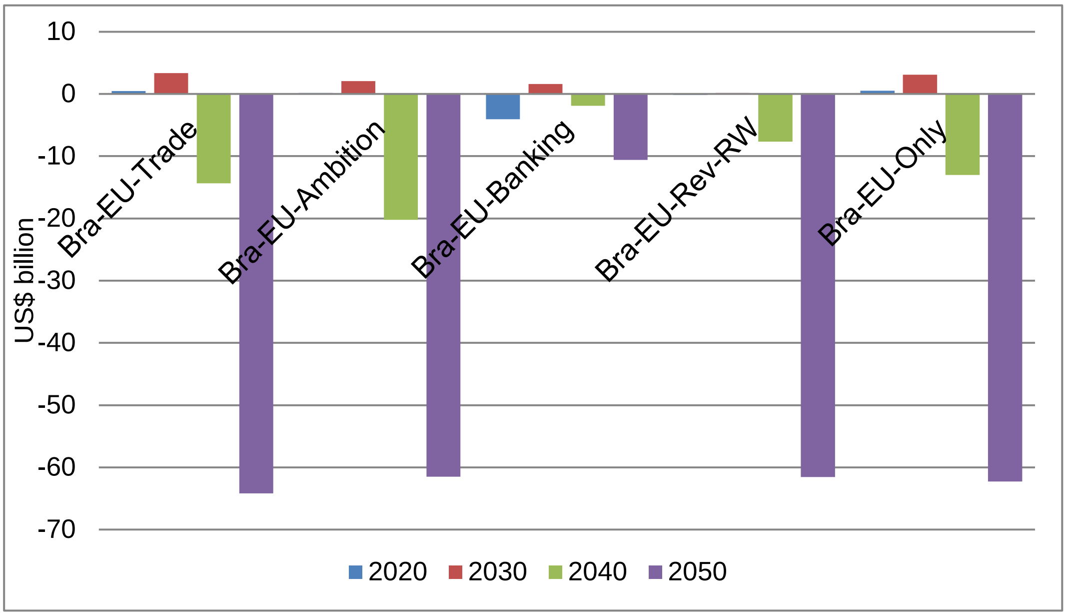
Similar aggregated mitigation of the sectoral ETS is observed if the ETS linkage is designed without the use of flexible mechanisms or climate policies in other regions, with the level of emissions in both cases being 47% lower than the No-Policy scenario. This indicates that the positive environmental effects realised in Brazil and Europe, of adopting an integrated price-based climate policy, do not depend on commitments from other regions.

Results also highlight that inter-temporal permit trading appears to provide strong incentives for early action, but at the risk of surrendering additional allowances in the future. In other words, it may create an over-allocation in subsequent periods and therefore, limited reductions. In fact, it demonstrated the ability to foster carbon price stability over the period, being mostly indicated for the period 2040-2050 when resulting carbon prices are very high in other linking scenarios.

If trading is allowed between the Brazilian sectoral ETS and the European system, Brazil displays a net importer profile of carbon permits in the first two decades, as displayed in Figure 3, in the form of positive values. Financial transfers from the Brazilian covered sectors to Europe range from US$0.2 to US$3.4 billion in the 2020-2030 period, corresponding to approximately 23.4, 14.7, 9.2, 1.1 and 22.8 million tonnes of CO_2 imported in 2030 according, respectively, to the Bra-EU-Trade, Bra-EU-Ambition, Bra-EU-Banking, Bra-EU-Rev-RW and Bra-EU-Only scenarios.

Figure 3

Total financial transfers of CO_2 permits (in 2007 US$ billion)



A long-term linkage with a developed system such as the EU ETS implies to Brazil an emissions reduction of approximately 60% compared to autarky, totalling on average 70 million tonnes less in all linking scenarios. The only exception is the Bra-EU-Banking link, in which there is just a 23% decrease in ETS emissions relative to Bra-ETS. In this case, permits are mostly supplied by Brazil, since abatement options or technological alternatives to mitigate become more available there, thereby receiving between US$1.9 and US$20.2 billion in 2040 and US$10.6 and US$64.2 among the simulated scenarios in 2050.

From the scenarios analysed, an inter-jurisdiction pattern can be detected, i.e. emissions reductions are transferred from Europe to Brazil by 2030 and thenceforward the inverse takes place, with international trading generating monetary flows to Brazil. This is aligned to the literature, which generally portrays Europe as a buyer of emissions in carbon markets of either developed (Dellink *et al.*, 2014) or developing countries linkages (Gavard *et al.*, 2013; Gavard *et al.*, 2016; Doda and Taschini, 2016).

This trading pattern reveals some important insights about linking under the modelled circumstances. It suggests the level of ambition plays an important role towards defining winners and losers from the link, since Brazil and Europe's commitments are, at first, very alike. Even though the literature recommends the harmonisation of mitigation targets, accommodating developing countries into a linked-system of similar rigid commitments to a developed country may further unequal distribution, being therefore politically difficult to support in those countries. Further issues may arise from an economic perspective, not just from the method of allocating allowances, i.e. via auctioning, but also in view of the overall increase in electricity prices induced by the ETS policy, which is detrimental to consumers. Hence, it affects overall direct economic effects and other general equilibrium impacts, assessed here by welfare and GDP.

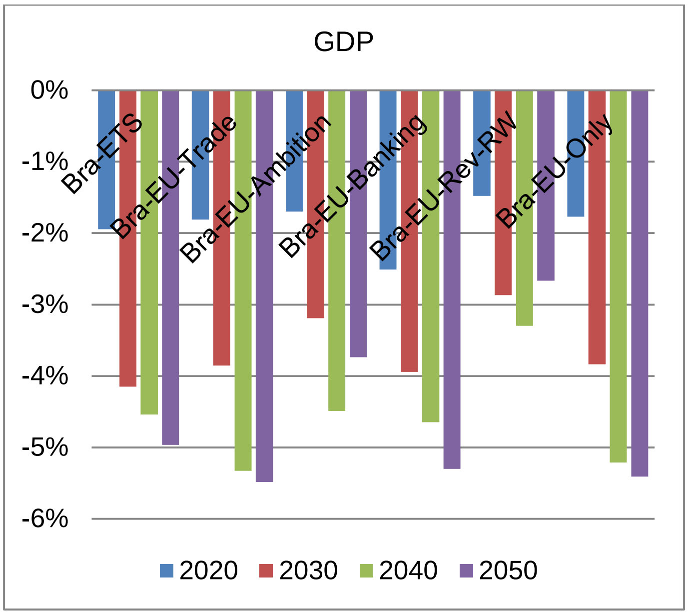
Welfare is a macroeconomic indicator to express the level of prosperity of economic agents. In EPPA6, it is equivalent to variations in consumption levels, which translate both income and relative price changes of the representative consumer, as an indicator for the induced change in utility. Additional economic cost of the sectoral ETS trading is evaluated in relation to impacts on GDP, that encompasses directly net export value (exports minus imports) and investments. These macroeconomic results are reported as percentage changes between policy scenarios and the No-Policy scenario.

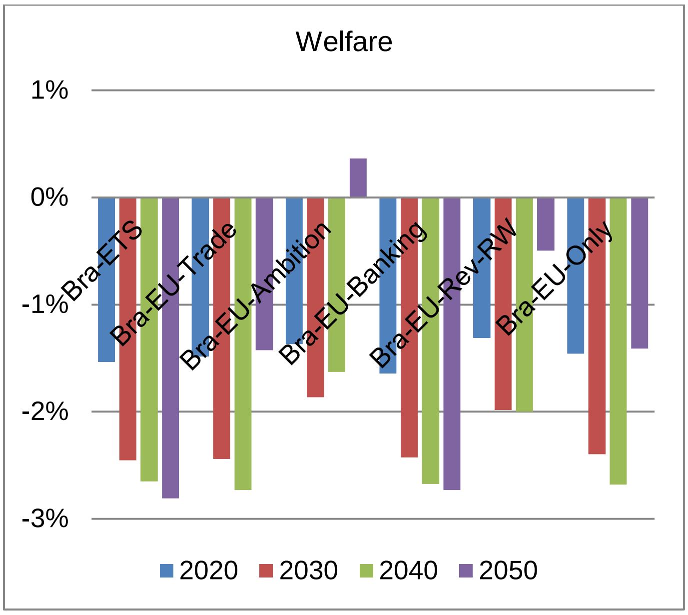
According to Figure 4, sharing the carbon constraint improves GDP and welfare in Brazil since it lowers the cost of the policy domestically and hence, the price to be paid by the economic agents. However, welfare reductions are lower than GDP's, although losses are very similar among the simulated scenarios. In the 2020-2030 horizons, the Bra-ETS presents the deepest decline of GDP and welfare, approximately 4.2% and 2.5%, respectively. This occurs due to the fact that the covered sectors face higher abatement costs as a result of the deep mitigation assumed for Brazil by 2030[17]. Moreover, the electricity sector is relatively low-carbon, and as a result has limited opportunities to cut emissions.

[17] However, it does not consider reductions from land use change and deforestation, very representative sectors of the Brazilian total emissions.

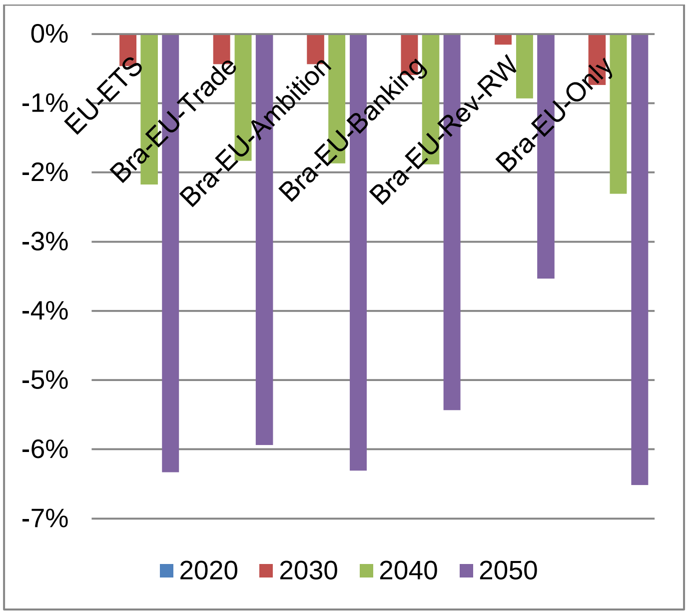
Figure 4

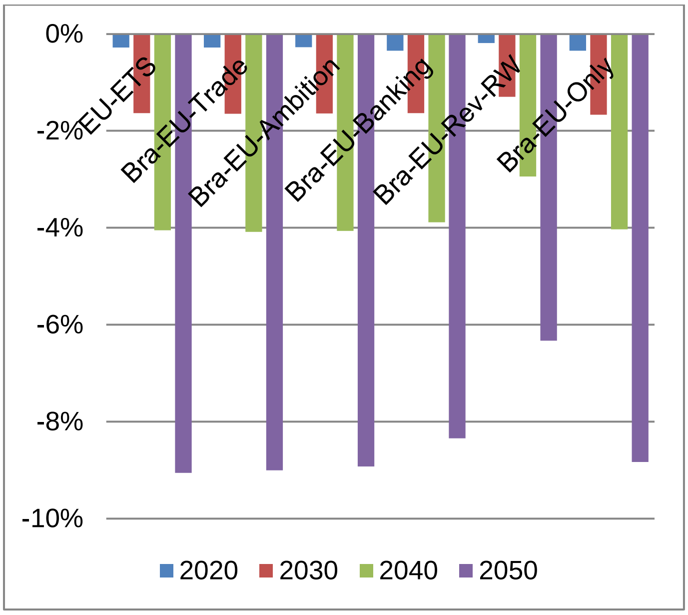
Changes in GDP and welfare in relation to BAU in (a) Brazil and (b) Europe





(a) (a)





(b) (b)

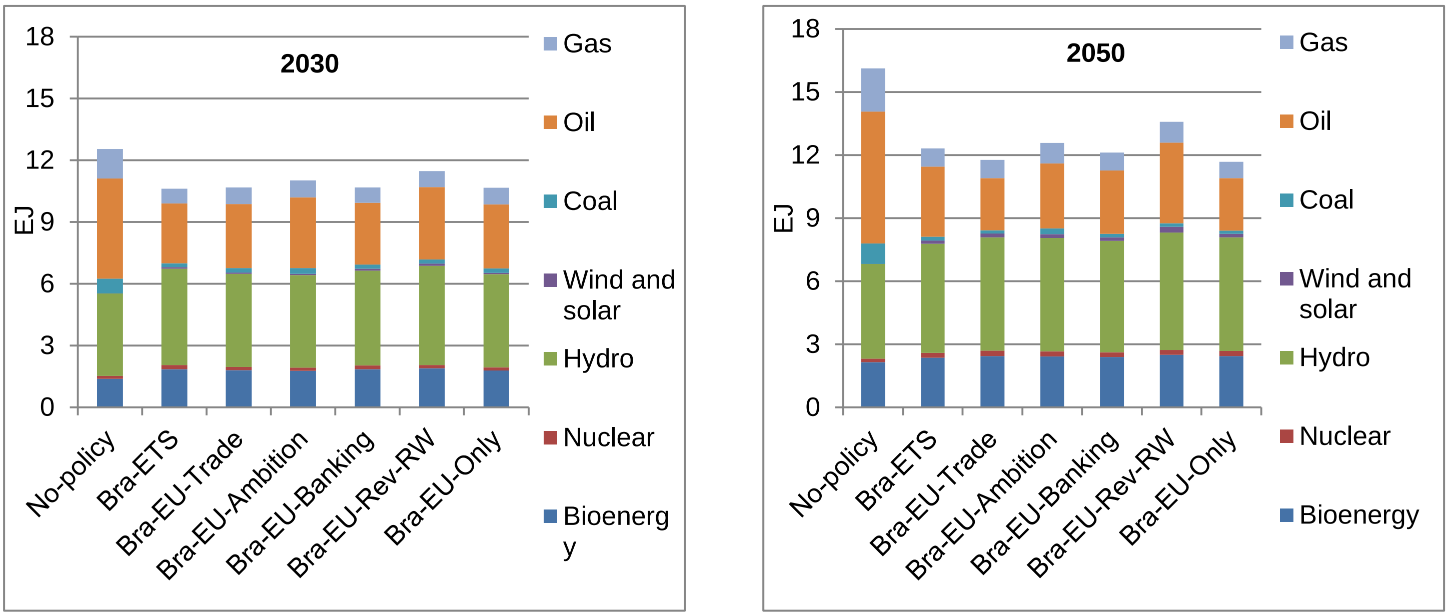
Conversely, if the link is agreed so that Brazil assumes a lower level of mitigation, economic costs drop and welfare losses are the smallest by 2030. Yet mitigation costs are the lowest when carbon revenues are reinvested back into alternative technologies, namely the production of renewable energy in the Brazilian economy. In the long term, GDP losses range between 2.7% and 5.5%, being less negatively impacted in the Bra-EU-Ambition and Bra-EU-Rev-RW scenarios by 2050. Compared to No-Policy levels, welfare is highly impacted by a domestic ETS or a linked system in which allowances can be banked over periods. Again, whether or not other regions commit, a linkage with basic ETS design yields the same costs for the economy and society to meet the mitigation target in the long term. However, if Europe agrees with a lower ambition, Brazil benefits by a 0.5% gain in welfare.

Potential revenues along with the prospects of associated cost savings can be a very attractive condition for Brazil to agree on the link. However, considering that the Brazilian electricity sector is already significantly decarbonised, with alternative energy comprising 51% of total energy used, the challenge is to move further towards increasing the share of low-carbon sources that can compete with fossil fuel-based power, especially if carbon emitters face an appropriate carbon price. In fact, Brazil is explicitly keen to strengthen its share of renewable energy in the energy mix, as stated in the NDC for the Paris Agreement.

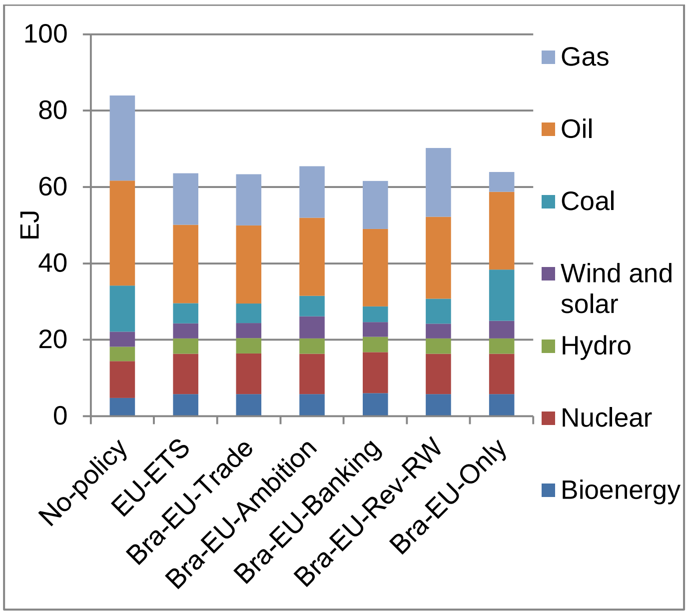
Policies that place a price on carbon are important drivers for the adoption of environmentally friendly technologies as well as being a stimulus for low-carbon innovation (Dechezleprêtre *et al.*, 2016). Therefore, it tends to enhance substitution from a polluting economy towards a more decarbonised one by altering the demand for fossil fuels, thereby changing the energy use profile. Figure 5 (a) shows the Brazilian energy mix, which includes primary and alternative energy use for 2030 and 2050. In the energy mix, hydro and oil predominate in Brazil, corresponding to approximately 40% and 30% of total energy, respectively, in the simulated scenarios. Total use of energy is, on average, 10.7 EJ in 2030 and 12 EJ in 2050.

Figure 5

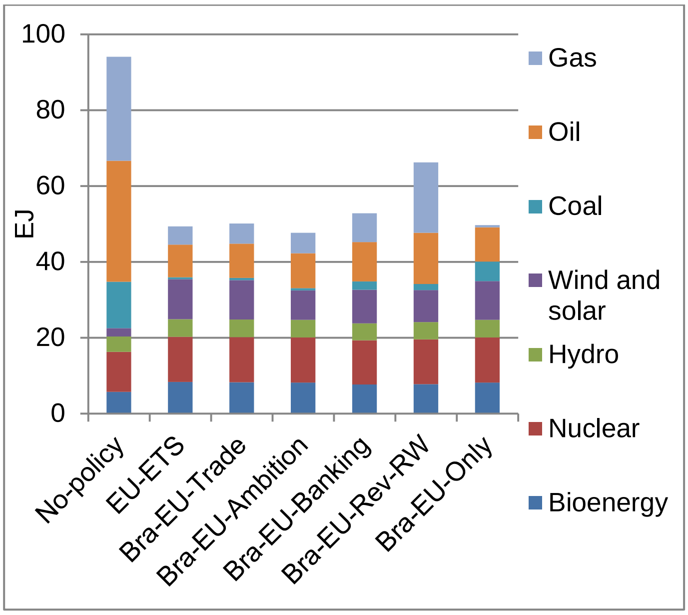
Energy profile of (a) Brazil and (b) Europe in 2030 and 2050



(a) (a)



(b)



(b)

As the sectoral ETS progresses over time, the relevance of low carbon technologies becomes even more evident relative to fossil fuel-based primary energy. For instance, the share of coal decreases by 69% in the Bra-EU-Trade and Bra-EU-Only scenarios, with a further decrease of 73% when flexible arrangements are incorporated into the system (i.e. banking or revenue recycling), and with a decrease of 70% if Brazil is less ambitious in 2030. Nevertheless, in this first decade, the Bra-ETS promotes the deepest substitution towards low-carbon energy, with an alternative energy share increase to 64% of the energy mix, which is primarily due to the effort required to meet the mitigation target without any cooperation.

Among all policy scenarios simulated, whereas hydroelectricity power in Brazil faces an increment of approximately 13%, renewables (wind and solar) rise more than 6000% in relation to No-Policy in 2030. Proportionally, this is still a small amount of electricity since it corresponds, on average, to only 0.09 EJ of the 6.5 EJ of alternative energy in the scenarios. The use of revenue recycling in Brazil is fundamental, particularly because it supports the decarbonisation of the energy sector the most. Similarly, the long term effect is driven by a lower demand for fossil-fuels, where primary energy use is between 3.4 EJ and 5 EJ in the policy scenarios, instead of 9.3 EJ without any mitigation target. The greatest substitution effect is verified in the Bra-EU-Rev-RW in 2050.

The European energy mix relies heavily on oil, gas, coal and nuclear energy, as depicted in Figure 5 (b). If there is no climate policies implemented, Europe uses a total of 82 EJ in 2030, where primary energy corresponds to 61.9 EJ and low-carbon technologies account for only 25% of the total. Technological changes are prompted by the EU ETS but linking to Brazil extends the energy substitution effect by 2030. Although fossil fuel energy still prevails, there is a growth in alternative energy by 10% in the EU-ETS, Bra-EU-Trade and Bra-EU-Rev-RW scenarios, and 12%, 13% and 18% in the Bra-EU-Banking, Bra-EU-Only and Bra-EU-Ambition scenarios relative to No-Policy in 2030.

Under the proposed sectoral design, linkage enhances technological changes in Europe so that in the long term there is a substitution effect towards low-carbon sources. Among them, bioenergy and renewables use surpasses the increase in hydro and nuclear. On the other hand, the greatest reductions occur in coal and gas use. Fossil-fuel substitution is more pronounced in autarky, where alternative energy represents 72% of the energy profile, with the share of oil being the smallest amongst scenarios.

Results suggest that the linking of an emerging sectoral ETS from a developing country, such as Brazil, to an established scheme such as the EUETS, can to a certain extent lead to welfare benefits for the involved jurisdictions. The linkage modelled in this paper underlines that an international ETS that recycles revenue from trading towards renewable energy production would be the most cost-effective option in terms of economic performance and effects on welfare. Moreover, a trade deal with less ambitious mitigation goals implemented in Brazil, yields a more cost-effective option.

4. CONCLSIONS

International cooperation through carbon pricing has become an important framework to address climate change, as highlighted in the Paris Agreement. In light of that, both developed and developing regions are encouraged to adopt market measures in the future, with flexibility to determine the role carbon prices play in the policy mix. With the number of Emissions Trading Schemes increasing around the world, the question of whether these schemes should be linked is relevant.

Experience shows that an ETS aggregating all sectors is still technically unfeasible. Since Brazil is still discussing the implementation of carbon pricing mechanisms, we made assumptions on the ETS design features in line with the EU ETS characteristics, as it is the most consolidated system. To comply with the NDC, we applied a sectoral ETS regulating electricity and energy-intensive sectors along with a supplementary policy on non-ETS sectors, in order to mimic abatement in those sectors, and to prevent leakage. To evaluate competitiveness issues associated with carbon leakage towards other regions, we implemented two scenarios, one whereby that same hybrid policy is applied to other jurisdictions of the model, and the other where no hybrid policy is applied. Results indicate that there is no material impact to the linkage in this instance, irrespective of whether or not climate policies are implemented in other jurisdictions.

This research serves as a basis to evaluate ETS policy proposals among consolidated systems in developed regions and emerging sectoral ETS from developing countries. We consider Europe, as a candidate to link with Brazil due to historical and economic relations. Our simulations include an autarky scenario for Brazil and Europe in addition to five linkage scenarios (Bra-EU-Trade, Bra-EU-Ambition, Bra-EU-Banking, Bra-EU-Rev-RW, Bra-EU-Only).

Results demonstrate that differences in carbon prices are eliminated through the link, and Brazil benefits from a lower carbon price if it links to Europe in the 2020-2030 period. In this case, carbon prices equalise at approximately US\$140/tCO_2. The highest price among linked scenarios in 2030 is US\$173/tCO_2, corresponding to the ETS design where allowances can be banked and carried forward over periods. Conversely, Europe is better off in the 2035-2050 horizon, as trading with Brazil allows to share a carbon price of approximately US\$882/tCO_2, 55% lower than in the EU ETS alone, and to comprise a wider abatement effort.

However, the costs for meeting the climate obligations through trading in both regions are still very high, at US\$840/ tCO_2 on average by 2050. Although this could facilitate emissions reductions, it implies large effects in terms of GDP and welfare, particularly for Europe. In the context of expected price increases, it is worthwhile to consider banking, at least in the long run, to hedge against this future price change. Compared to other scenarios, GDP and welfare losses are lower, 5.4% and 8.3% lower respectively by 2050. Another alternative is to include revenue recycling in the ETS design, since it reduces the most negative economic effects in Europe, approximately 0.2% and 3.5% of GDP loss, and 1.3% and 6.3% of welfare loss in 2030 and 2050, respectively.

The observed significant costs of the policy result from the stringency level of targets adopted in both entities. The level of effort required for Brazil to achieve the proposed climate commitments appear to be higher than in Europe up to 2030. Results from the Bra-EU-Ambition give a clear example on this. When the link is negotiated to accept lower mitigation targets in Brazil, GDP declines 3.2% and 3.7% in 2030 and 2050 respectively, whereas welfare decreases by 1.9% in 2030 but grows 0.4% in 2050. Similar effects occur in the Bra-

EU-Rev-RW scenario, where there is a smaller reduction in both GDP and welfare levels, 2.9% and 2% in 2030, and 2.7% and 0.5% in 2050, respectively.

In this investigation, the difference in stringency of ETS targets between a developed and developing region implies different trading patterns over the period. From 2020-2030 Brazil assumes an importer-oriented profile, with payments for allowances accruing to Europe of approximately US$3 billion. Thereafter, Brazil becomes a net exporter of allowances, which is aligned to the literature, i.e. developing countries pursuing a permit exporter pattern. Under this perspective, transfers from Europe total more than US$60 billion.

To a certain extent, this financial flow compensates the early costs incurred during the linkage. At the same time, it is environmentally effective, due to the high abatement levels achieved, along with the fossil-fuel substitution effect it triggers in both countries, as evidenced in the paper.

In future policy iterations, the link could envisage the incorporation of additional sectors, such as land use change, and other Greenhouse Gases (GHGs), particularly if one jurisdiction presents a relatively decarbonised energy mix, such as Brazil. Once the sectoral ETS progressively mitigates emissions, the focus will shift increasingly towards reducing emissions from other sectors. Thereupon, strengthening the climate package with domestic carbon taxes to curb emissions outside the ETS is rather necessary as well as regulatory and technology policies to enhance innovation, or to compensate those sectors disproportionately affected. These additional factors are relevant for further analysis.

Through this paper we contribute to the literature by showing that, linking an existing developed ETS system to a developing country emerging ETS system, can promote mitigation cost-effectively, whilst curbing emissions and changing energy use patterns if the correct ETS design is implemented. The approach modelled does not consider the costs or benefits associated with avoiding climate change, climate adaptation, or for other policies to support technological change at the intra-industry level. However, it does configure a first approximation on how developing countries could design their ETS, and incorporate carbon pricing and trading arrangements, with the aim of reducing emissions in as cost effective a fashion as possible.

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REFERENCES

Anthoff, D., Tol, R., 2011. **The Uncertainty about the Social Cost of Carbon**: A Decomposition Analysis Using FUND. Climate change, vol. 117 (3).

Armington, P., 1969. **A Theory of Demand for Products Distinguished by Place of Production**. Staff Papers (International Monetary Fund), *v*ol. 16 (1), pp. 159-178.

Aguiar, A., Narayanan, B., McDougall, R., 2016. **An Overview of the GTAP 9 Data Base**. Journal of Global Economic Analysis, vol 1 (1), pp. 181-208.

Bodansky, D., Hoedl, S.A., Metcalf, G., Stavins, R., 2014. **Facilitating Linkage of Heterogeneous Regional, National, and Sub-National Climate Policies Through a Future International Agreement.** Cambridge, Mass.: Harvard Project on Climate Agreements.

Boden, T.A., Marland, G., Andres, R.J., 2010. **Global, Regional, and National Fossil-Fuel CO2 Emissions**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA, 2010.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R., 1998. **GAMS A Users Guide**. GAMS Development Corporation, Washington D.C.

Burtraw, D., Palmer, K., Munnings, C., Weber, P., Woerman, M., 2013. **Linking by Degrees:** Incremental Alignment of Cap-and-Trade Markets. RFF Discussion Paper 13-04, 2013.

Chen, H., Paltsev, S., Reilly, J.M., Morris, J.F., Babiker, M.H., 2015. **The MIT EPPA6 Model:** Economic Growth, Energy Use, and Food Consumption**.** Report: no. 278. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change.

Dellink, R.B., Jamet, S., Chateau, J., Duval, R., 2014. **Towards Global Carbon Pricing:** Direct and Indirect Linking of Carbon Markets. OECD Environmental Working Paper No.20.

Dimaranan, B.V., Mcdougall, R.A., 2006. Guide to the GTAP Data Base. In: Dimaranan, ed., **Global Trade, Assistance, and Production:** The GTAP6 Data Base. Center for Global Trade Analysis, Purdue University, West Lafayette.

Doda, B., Taschini, L., 2016. **Carbon dating:** When is it beneficial to link ETSs? Centre for Climate Change Economics and Policy, Working Paper No. 234.

Domingues, E.P., Magalhães, A.S, Carvalho, T.S., 2014. **Política industrial e os custos de redução de emissões de Gases de Efeito Estufa.** Prêmio CNI de Economia.

Edenhofer, O., Carraro, C., Hourcade, J.C, Neuhoff, K., Luderer, G., Flachsland, C., Jakob, M., Popp, A., Steckel, J., Strohschein, J., Bauer, N., Brunner, S., Leimbach, M., Lotze-Campen, H., Bosetti, V., de Cian, E., Tavoni, M., Sassi, O., Waisman, H., Crassous-Doerfler, R., Monjon, S., Dröge, S., van Essen, H., del Río, P., Türk, A., 2009. **The Economics of Decarbonization**. Report of the RECIPE project. Potsdam-Institute for Climate Impact Research: Potsdam.

Ellerman, D., Valero, V., and Zaklan, A., 2015. An Analysis of Allowance Banking in the EU ETS. EUI Working Paper RSCAS 2015/29.

European Commission (EU), 2016. **EU Reference Scenario 2016** – Energy, transport and GHG emissions - Trends to 2050.

Frankhauser, S., Hepburn, C., 2010. **Designing carbon markets**. Part I: Carbon markets in time. Energy Policy, v. 38, p. 4363 – 4370.

Feijó, F. F., Porto Júnior, S. S., 2009. **Protocolo de Quioto e o bem–estar econômico no Brasil:** uma análise utilizando equilíbrio geral computável. Análise Econômica, João Pessoa, v. 27, n. 51, p. 127-154.

França, F.P., 2012. **Impactos econômicos de políticas climáticas no Brasil, nos EUA e UE**. 126p. Dissertação (Mestrado em Economia Aplicada) – Faculdade de Economia, Administração e Contabilidade de Ribeirão Preto, Universidade de São Paulo, Ribeirão Preto.

Foley, D., Rezai, A., Taylor, L., 2013. **The social cost of carbon emissions**: Seven propositions. Economics Letters, vol. 121 (1), pp. 90-97.

Gavard, C., Winchester, N., Paltsev, S., 2016. **Limited trading of emissions permits as a climate cooperation mechanism?** US–China and EU–China examples. Energy Economics 58, 95–104.

Gavard, C., Winchester, N., Paltsev, S., 2013. **Limited sectoral trading between the EU ETS and China**. MIT JPSPGC, Report 249.

Grosjean, G., Acworth, W., Flachsland, C., and Marschinski, R., 2014. **After monetary policy, climate policy**: is delegation the key to EU ETS reform? Climate Policy, 1:1–25.

Gurgel, A. C., 2012. **Impactos da economia mundial de baixo carbono sobre o Brasil**. Anais da ANPEC.

Gurgel, A. C., Paltsev, S., 2014. **Costs of reducing GHG emissions in Brazil**. Climate Policy, v. 14, p. 209 - 223.

Henriques, JR. M.F., 2010. **Potencial de redução de emissão de gases de efeito estufa pelo uso de energia no setor industrial brasileiro.** Tese de Doutorado, COPPE/PPE.

Hübler, M., Voigt, S., Löschel, A., 2014. **Designing an emissions trading scheme for China:** An up-to-date climate policy assessment. Energy Policy 75, 57–72.

Hotteling, H., 1931. **The Economics of Exhaustible Resources**. Journal of Political Economy, vol. 39, No. 2, pp. 137-175

International Energy Agency (IEA), 2012. **World Energy Outlook.** International Energy Agency, Paris, France.

Kollenberg, S., Taschini, L., 2016. **Emissions trading systems with cap adjustments.** Centre for Climate Change Economics and Policy, Working Paper No. 219.

Lucena, A. F.P, Clarke, L., Schaeffer, R., Szklo, A., Rochedo, P.R.R., Nogueira, L.P.P., Daenzer, K., Gurgel, A., Kitous, A., Kober, T., 2015. **Climate policy scenarios in Brazil:** A multi-model comparison for energy. Energy Economics, vol. 56, pp. 564-574.

Narayanan, G., Badri, T., Hertel, W., Walmsley, T.L., 2012. **GTAP 8 Data Base Documentation.** Chapter 1: Introduction. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, March.

Octaviano, C., Paltsev, S., Gurgel, A., 2016. **Climate change policy in Brazil and Mexico:** Results from the MIT EPPA model. Energy Economics, vol. 56, pp. 600-614.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Gurgel, A.C., Metcalf, G.E., Sokolov, A.P., Holak, J.F., 2007. **An Assessment of U.S. Cap-and-Trade Proposals.** Working Paper 13176. Cambridge, Massachusetts: National Bureau of Economic Research, June 2007.

Peñasco, C., Del Río, P., 2015**. The evolving EU ETS carbon pric**e. Issue paper for the Towards2030 project. Dialogue on a RES policy framework for 2030.

Rathmann, R., 2012. **Impactos da adoção de metas de redução de emissão de gases de efeito estufa sobre a competitividade de setores industriais energointensivos do Brasil.** Tese de Doutorado apresentada ao Programa de Planejamento Energético, COPPE/UFRJ, para obtenção do título de Doutor em Ciências do Planejamento Energético.

Riahi, K., Grübler, A., Nakicenovic, N., 2007. **Scenarios of long-term socio-economic and environmental development under climate stabilization.** Technological Forecasting and Social Change 74(7), 887–935, 2007.

Rutherford, T. F., 1999. **Applied general equilibrium modeling with MPSGE as a GAMS subsystem:** an overview of the modeling framework and syntax. Computational economics Kluwer academic publishers: 14, 1-46.

Silva, J. G, Gurgel, A. C., 2012. **Impactos econômicos de cenários de políticas climáticas para o Brasil.** Pesquisa e Planejamento Econômico, v. 42, n. 1.

Somanathan, E., 2008. What do we expect from an International Climate Agreement? A perspective from a low-income Country. Policy Brief, Harvard Project on Climate Agreements, Belfer Center, December 2008.

Wills, W., Lefevre, J., 2012. **The impact of a carbon tax over the Brazilian economy in 2030 - IMACLIM:** the hybrid CGE model approach. In: ISEE 2012 Conference – Ecological Economics and Rio+20: Challenges and Contributions for a Green Economy, 2012, Rio de Janeiro. Greening the Economy – Measuring green growth.